Boosting BSM Higgs discovery with jet substructure

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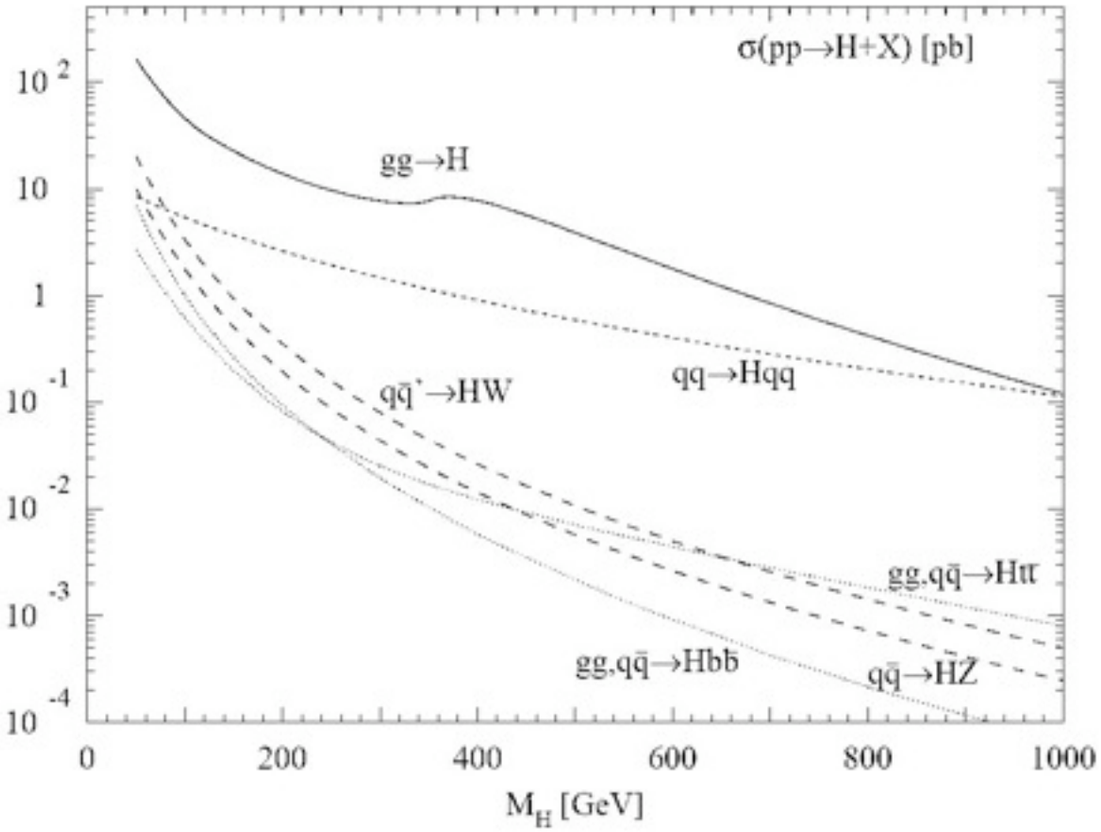
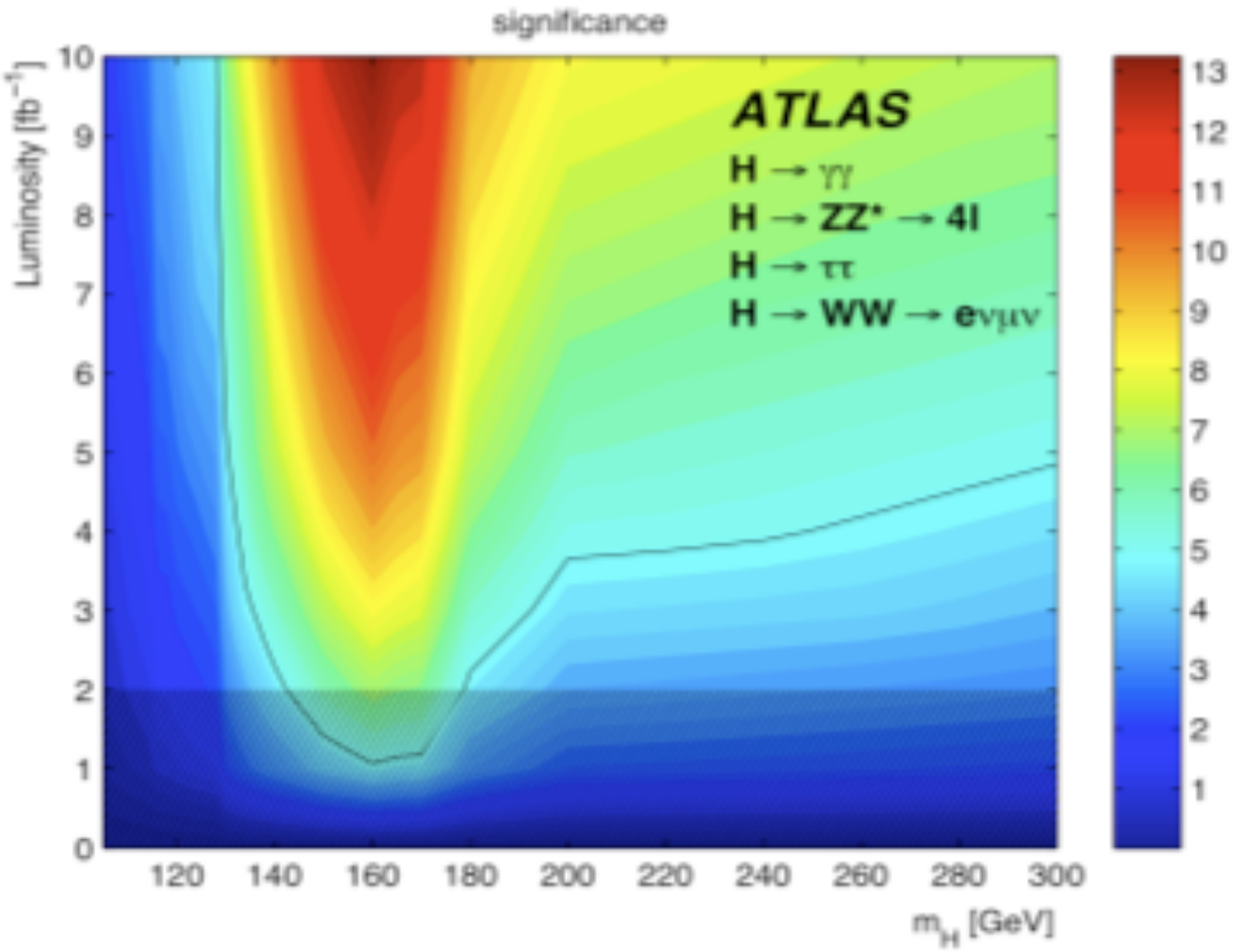
arxiv: 09124731

Fermilab, Feb 18th, 2010

Fermilab

Despite large LHC cross sections...



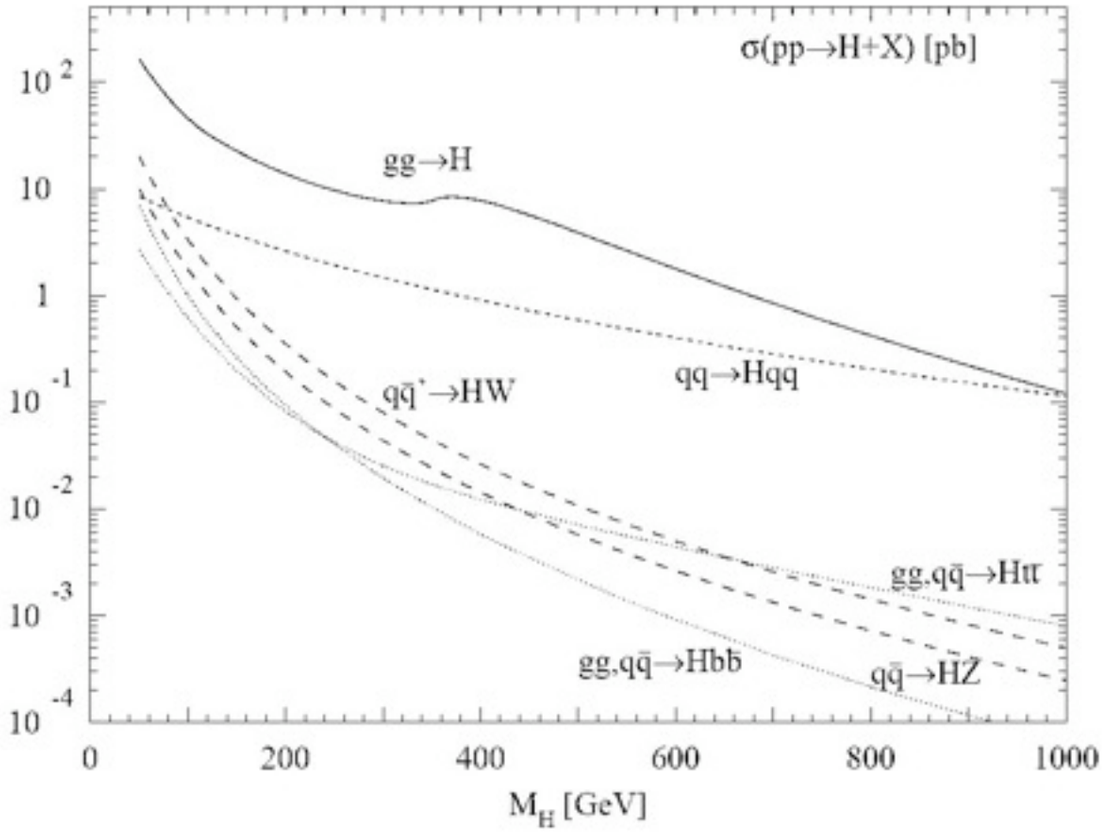


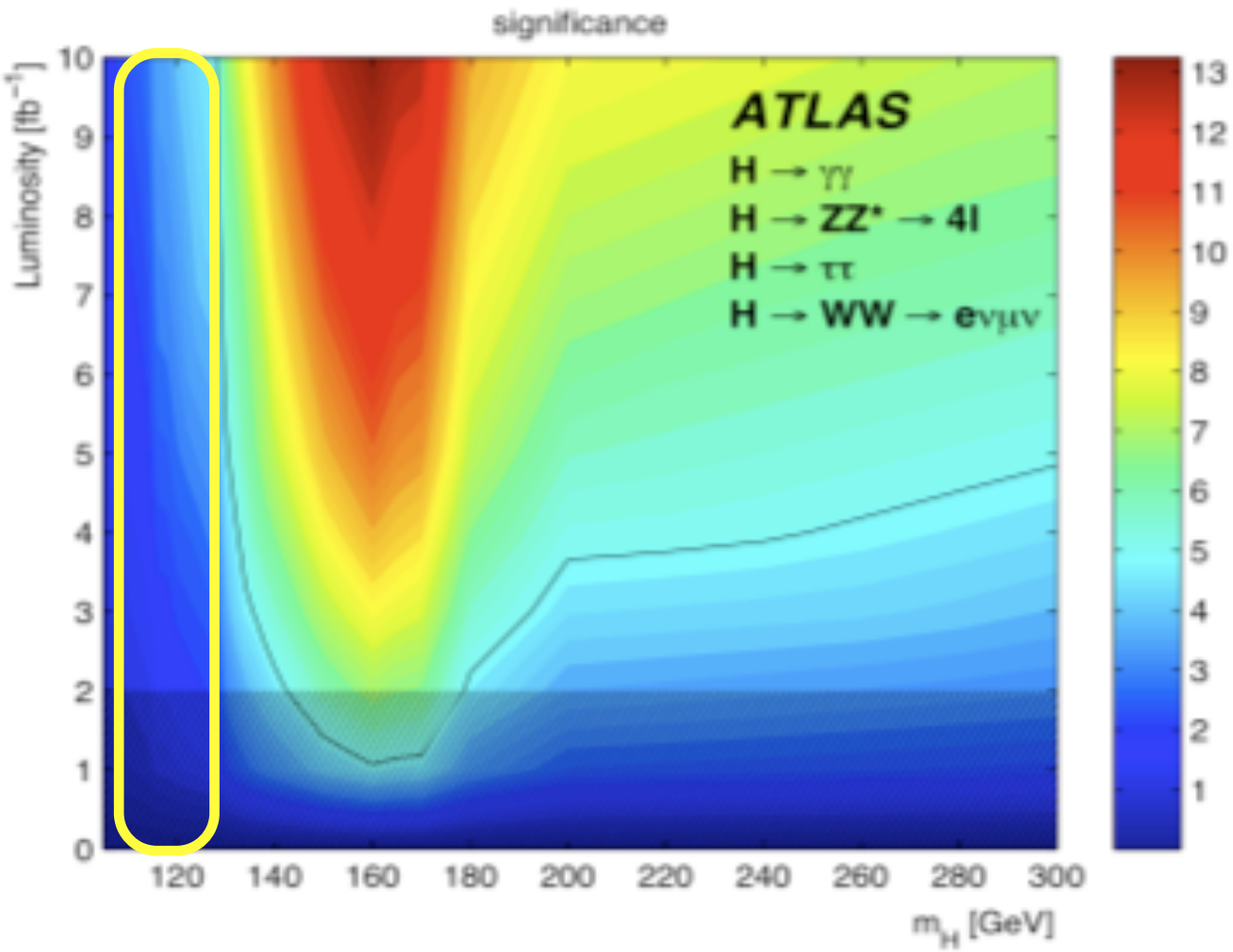
a light Higgs $m_h \sim 115 - 130\ \mathrm{GeV}$**, which decays primarily** $\sim 80\%$ **:**

$$h \longrightarrow \bar{b}b$$

will be difficult to find

Despite large LHC cross sections...





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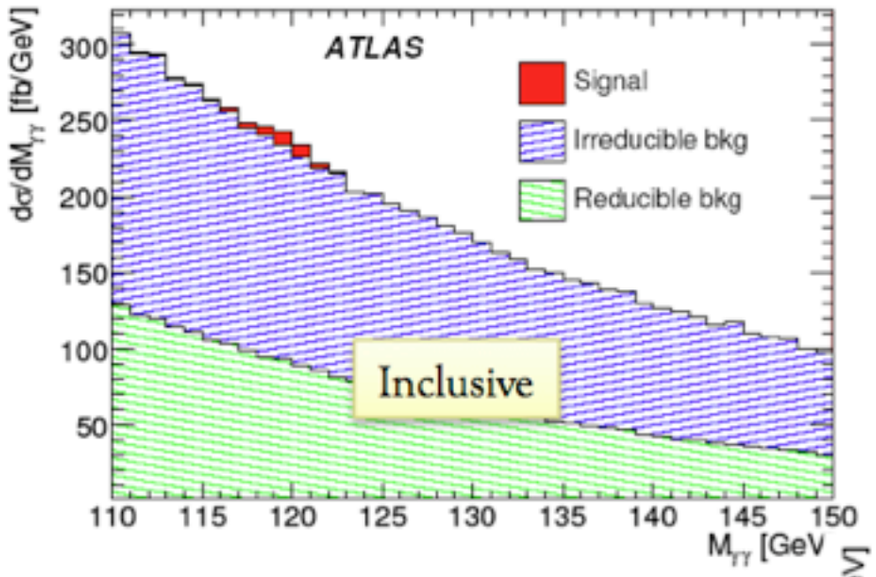
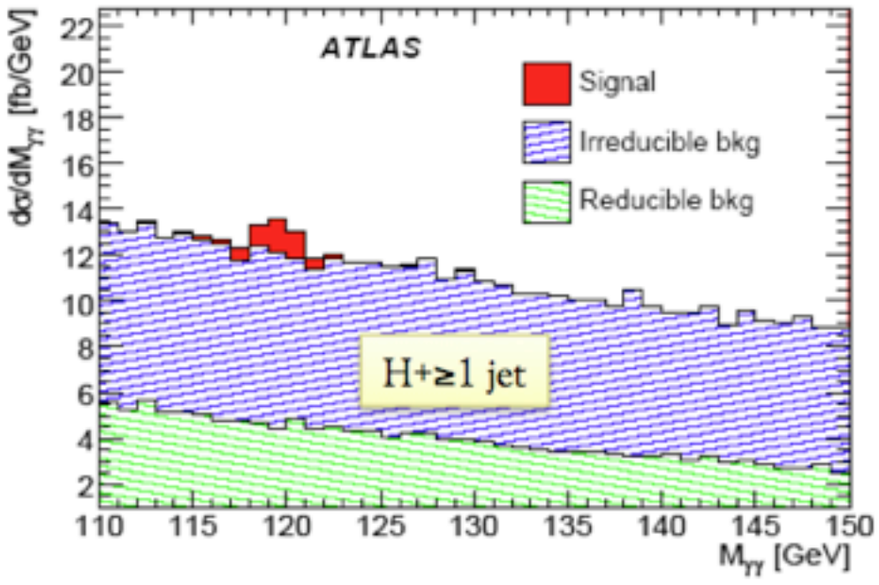
for the lightest mass range the most sensitive channel is $h \to \gamma\gamma$

- reconstruct the diphoton invariant mass peak, on top of continuum diphoton background
- ATLAS: inclusive diphoton and exclusive $\gamma\gamma + \text{jets}$ searches



for $\mathcal{L} = 10\ \text{fb}^{-1}$

$S/\sqrt{B} = 2.6$



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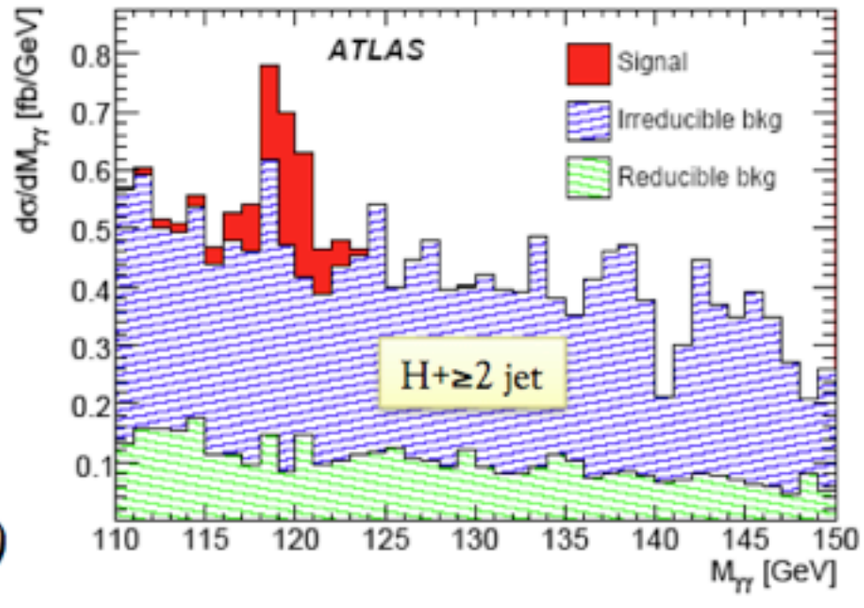

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source (ATL-PHYS-2008-258)

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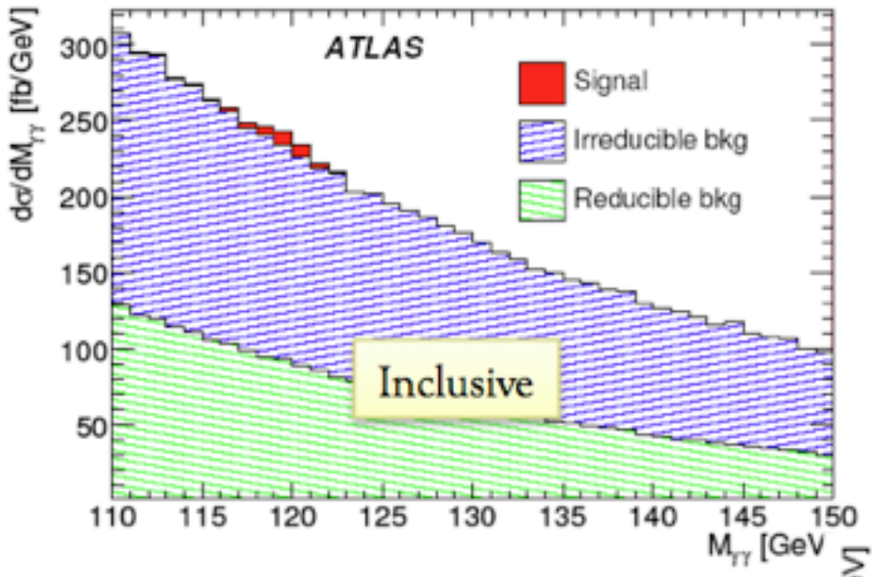

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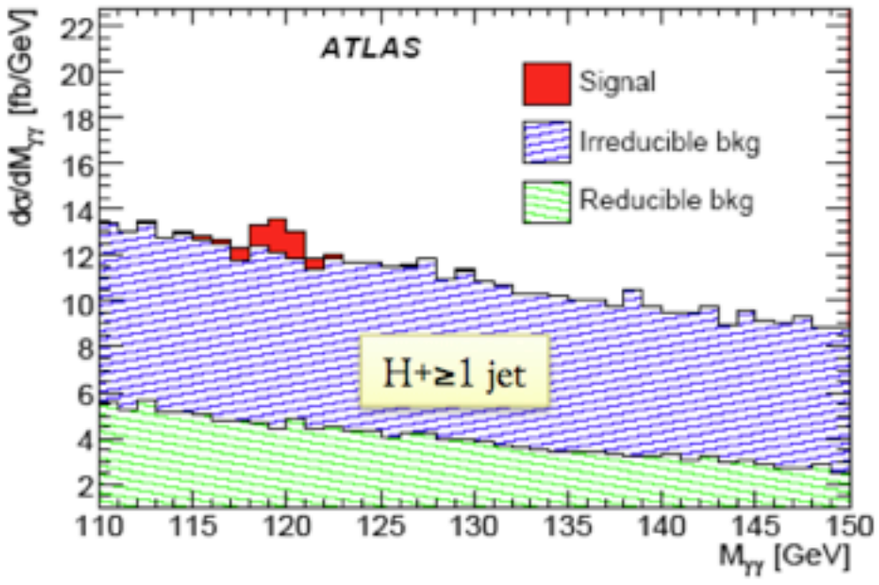

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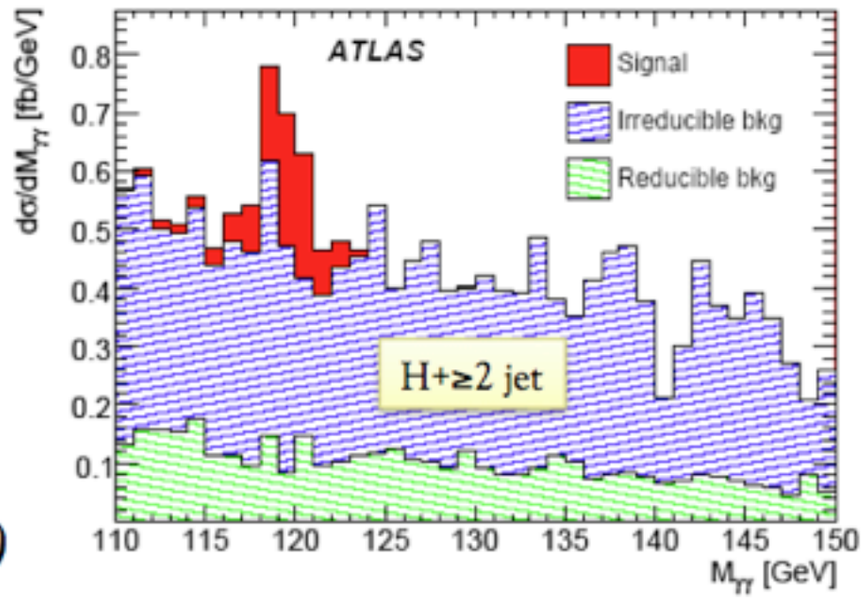


$hW(\ell\nu)/hZ(\ell\ell,\nu\nu)$

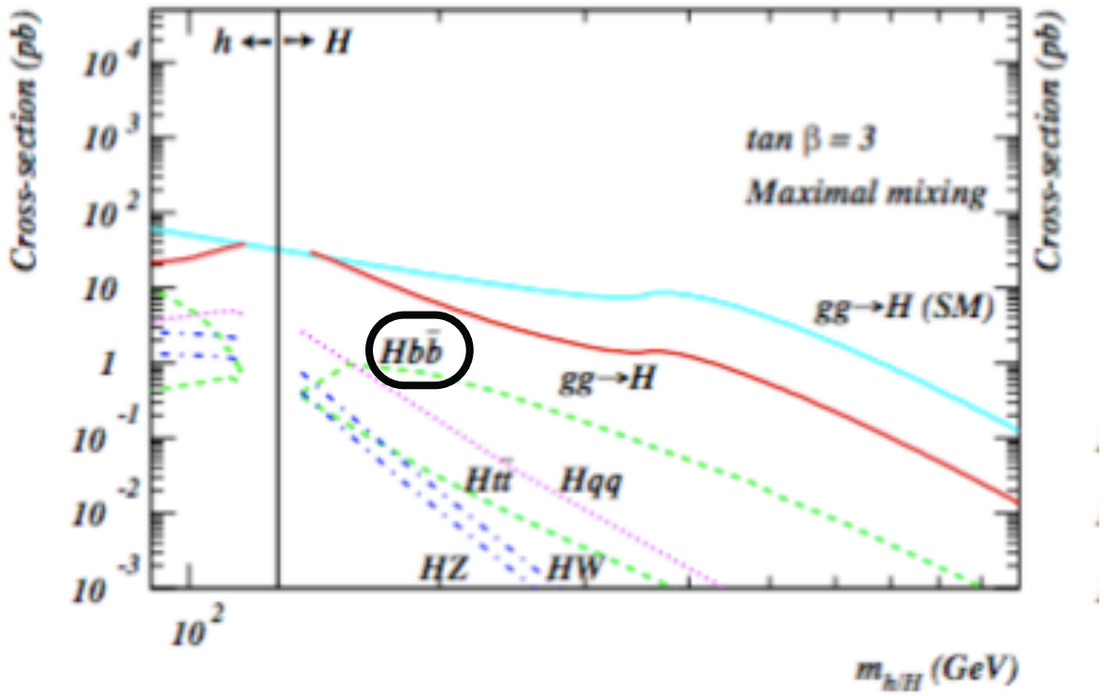
$h \to \tau\tau$

also contribute, but small

source (ATL-PHYS-2008-258)

Going beyond the SM... light Higgs still hard

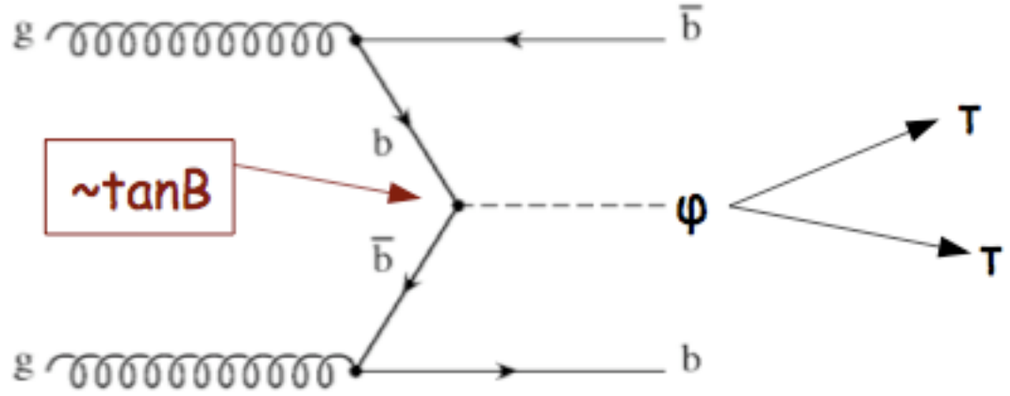
ex.) MSSM



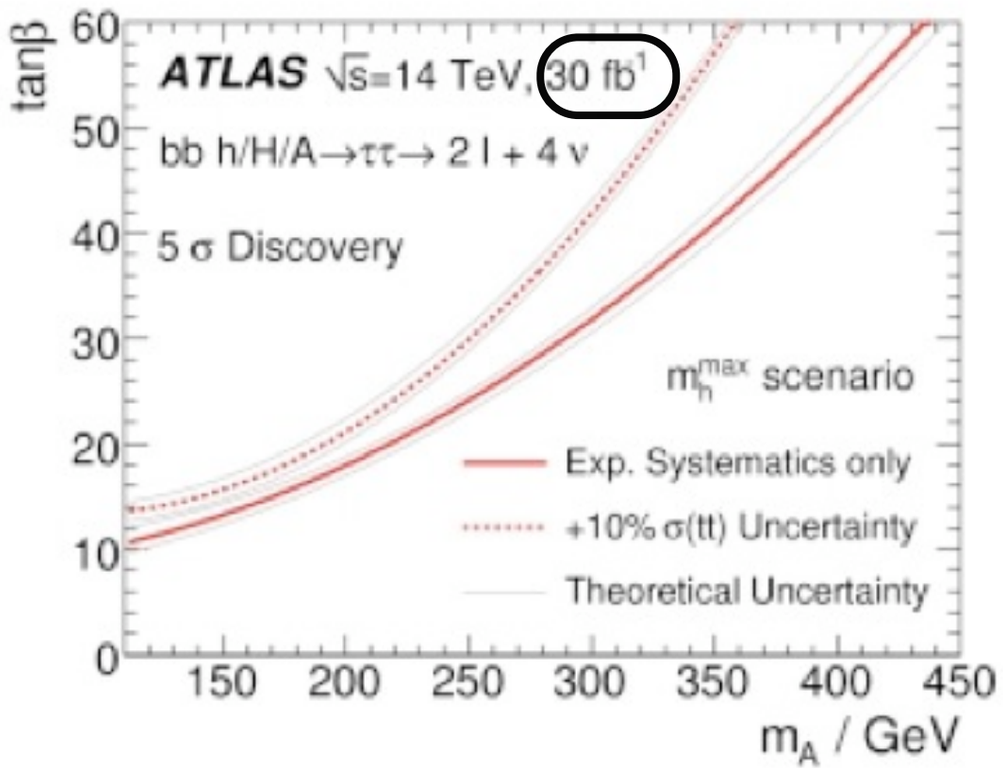
some enhancement, but only when m_A is small and $\tan\beta$ is large

flavor problems?

conventional MSSM light higgs search



$bb\,h/H/A \to 2l + 4\nu$



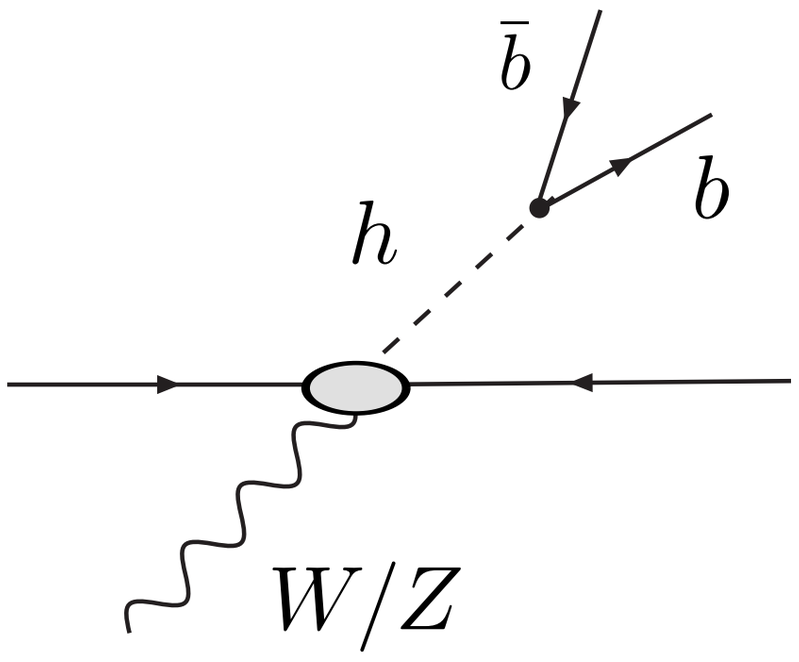
Recently, a new technique for light Higgses

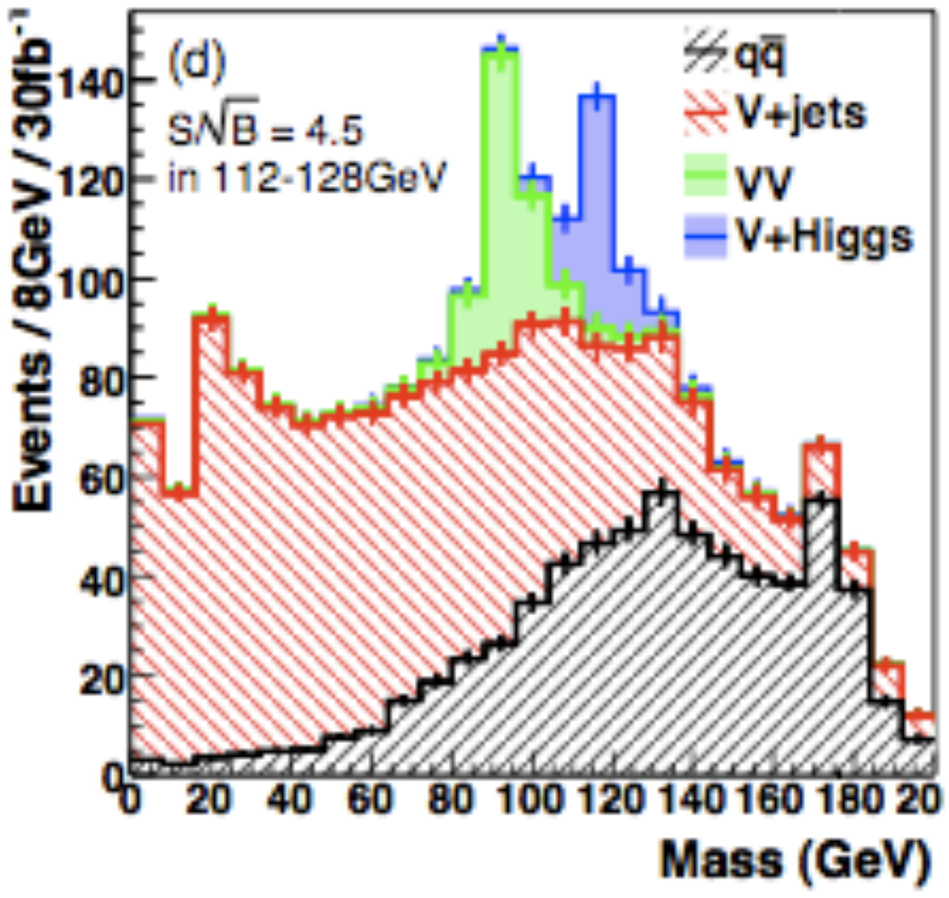
(Butterworth, Davison, Rubin, Salam '08)

In associated production of Higgs + Z,W: $W(\ell\nu)/Z(\ell\ell) + h(\bar{b}b)$

significance ~ 4.5 for $\mathcal{L} = 30\ \text{fb}^{-1}$ $\left(\sim 2.6 \text{ for } \mathcal{L} = 10\ \text{fb}^{-1}\right)$

obtained by focusing on
boosted Higgses , $p_{T,h} > 200\ \text{GeV}$





Recently, a new technique for light Higgses

Basic Idea:

signal: high $m_{b\bar{b}}$, $R_{b\bar{b}}$ depends on boost

background: high $m_{b\bar{b}}$ at large $R_{b\bar{b}}$

$$m_{ij}^2 \sim 2\, p_{Ti}\, p_{Tj}\, (R_{ij})^2$$

boosted regime: high $m_{b\bar{b}}$ smaller $R_{b\bar{b}}$

Boosted objects appear as a single 'fat jet' in the detector...

to dig out the b-jets from a 'fat jet' use recently developed

jet substructure techniques

Other Applications of Boosted analysis

- two-pronged decays (SM Higgs):

  Butterworth, Davison, Rubin, Salam (2008)

- three-pronged decays (boosted top):

  Kaplan, Rehermann, Schwartz, Tweedie (2007)
  Brooijmans (2008)
  Thaler and Wang (2008)
  Butterworth, Ellis, Rakhlev, Salam (2009)

- jet pruning/trimming:

  Ellis, Vermilion, Walsh (2009)
  Krohn, Thaler, Wang (2009)

Boosted Higgses

interesting new approach

BUT a bit limited in SM

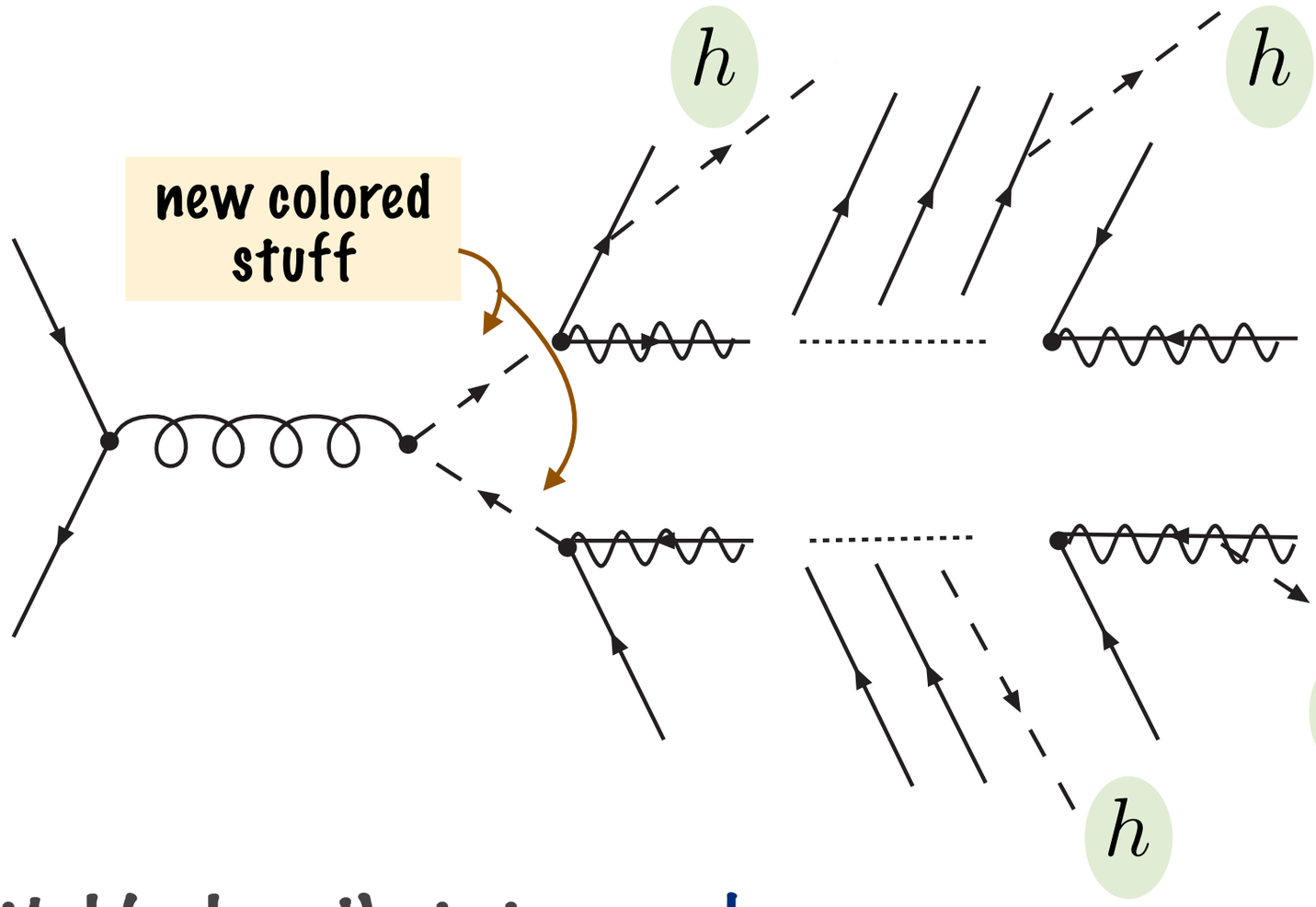
* boosted Higgs are rare in the SM: $\sim 5\%$ in $H + W/Z$

* need to trigger & suppress SM backgrounds: limited to W/Z leptonic decay modes

What about jet substructure analysis + BSM?

Higgs from BSM

BSM particles can decay to Higgses



= a new source of Higgses

initial (colored) states are heavy $(\sim \mathrm{TeV})$
while Higgs can be light

higher fraction of boosted Higgses

Higgs from BSM

If BSM contains new colored states, production at LHC is easily in the $\sim$ few pb range

comparable to or greater than
SM EW Higgs production

BSM production often comes with new, effective handles for suppressing SM backgrounds

$$\not{E}_T, \text{high} - p_T \text{ jets}, \ell, \gamma, H_T, \cdots$$

Higgses from BSM have all of the important ingredients for a successful substructure analysis

the plan:

Substructure Techniques + BSM = an opportunity for light Higgs discovery

Pick a new physics scenario with gives us a source of boosted Higgses

Use substructure techniques in these scenarios to combat backgrounds, both from the SM and from new physics

Adapt substructure to work in hectic, crowded BSM environments

Part I: SUSY sources of boosted Higgs

Though our techniques apply to a wide array of BSM scenarios, we'll look at (weak scale) SUSY

why SUSY?

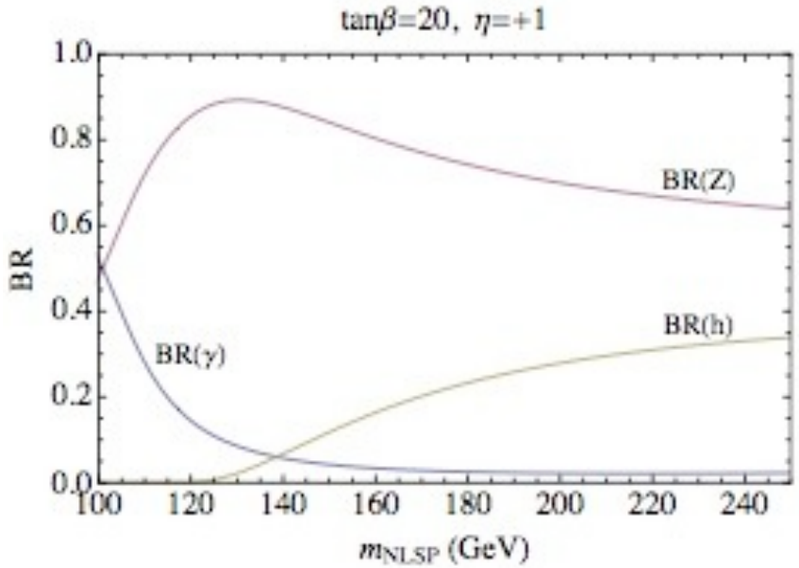
- MSSM Higgs has to be light $m_h \lesssim 130$ GeV, decays dominantly to $b\bar{b}$
- it has new colored particles (squarks, gluinos), which can be produced with large cross sections
- all events include $\not{E}_T$
- Higgs via various decays:

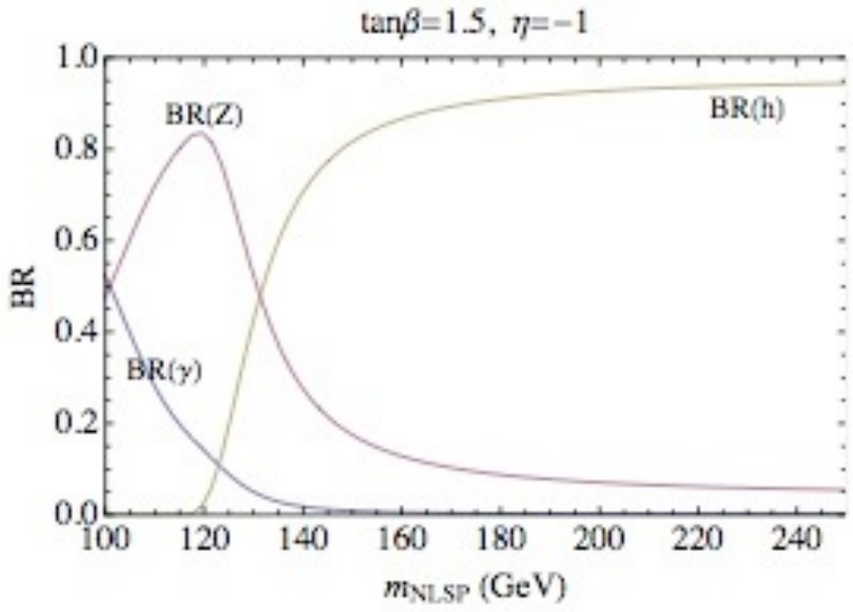
$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 + h \qquad \tilde{t}_{L,R} \to \tilde{t}_{R,L} + h$$

$$\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm + h \qquad \tilde{\chi}_1^0 \to \tilde{G} + h$$

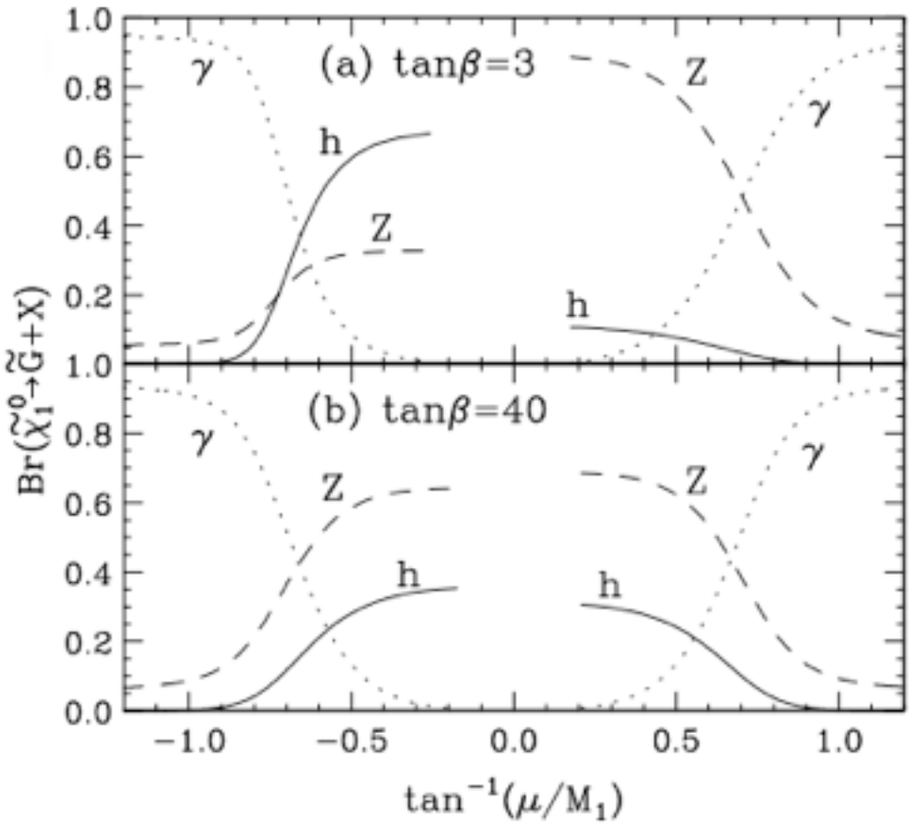
Neutralino Decays to Gravitinos

- happens when the scale of SUSY breaking is low (GMSB)
- decays of neutralinos governed by $M_1, M_2, \mu, \tan\beta$
- can get appreciable BR to Higgses when the lightest neutralino is primarily Higgsino $|\mu| \ll M_1, M_2$





(Meade, Reece, Shih '09)

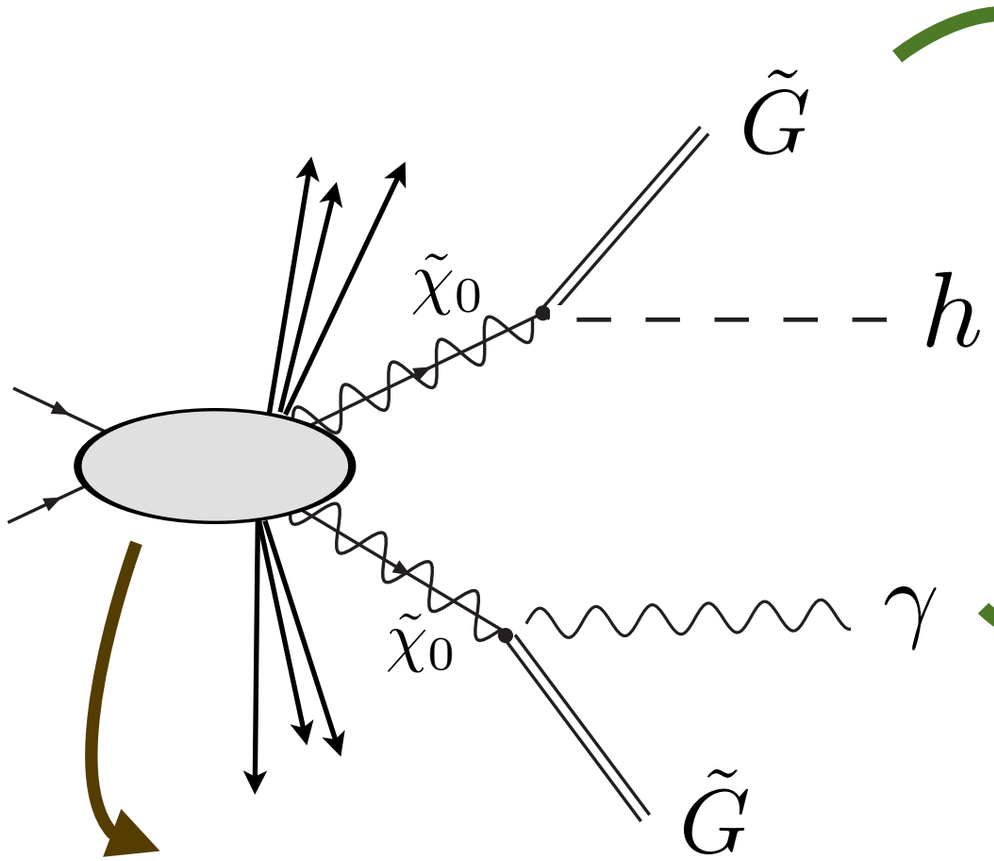


(Matchev, Thomas '99)

Why start with $\tilde{\chi}_1^0 \to \tilde{G} + h$?

- The mixed decay $\tilde{\chi}^0\tilde{\chi}^0 \to h + \gamma + \not{E}_T$

  has a smaller rate, but many advantages



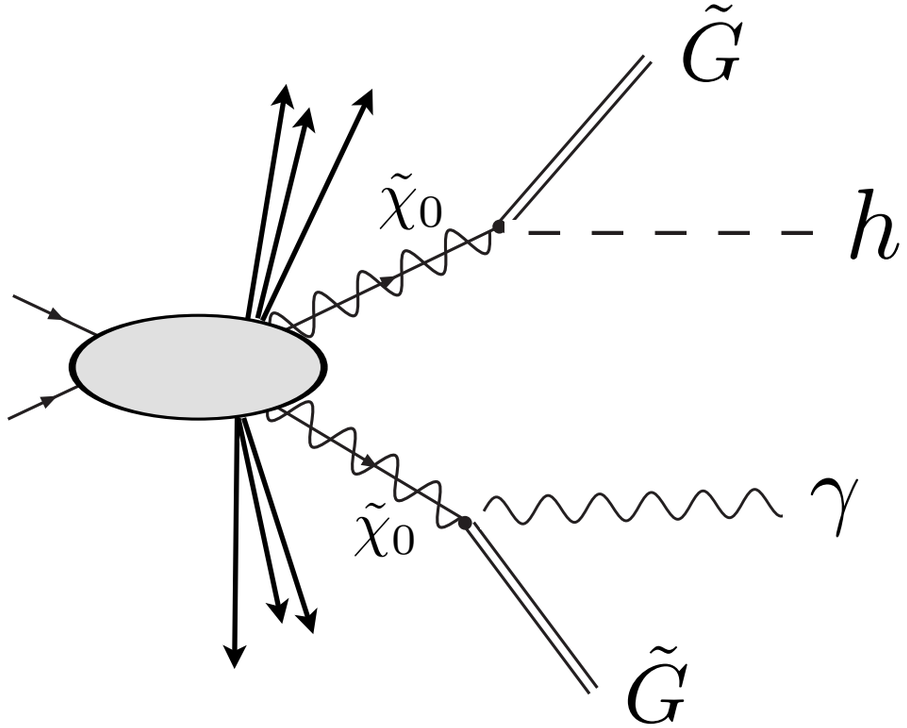
hard, isolated photon
plus large $\not{E}_T$
kills off much of the SM
background

heavier, colored sparticles control LHC production

- simplest BSM scenario we could think of to test jet substructure techniques on

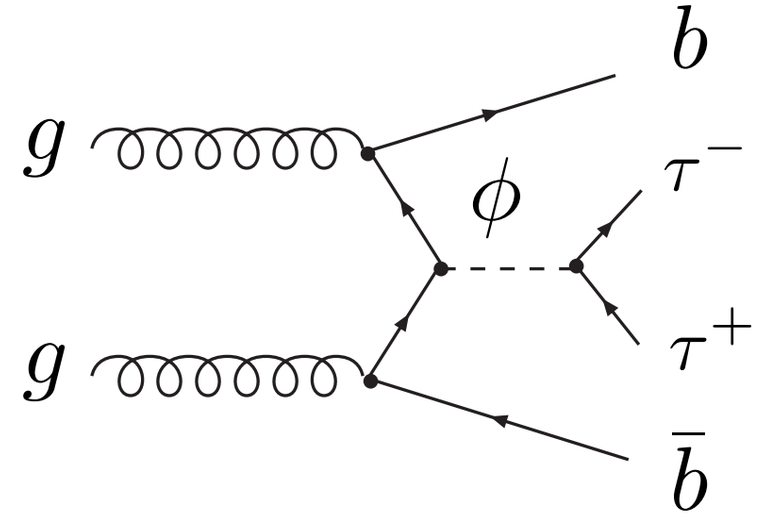
Higgses source comparison

how we want to look for the MSSM Higgs



- Higgses from sparticle decays
- big cross-section (inclusive SUSY prod.)
- all events have $\not{E}_T$, lots of extra jets
- SM and BSM backgrounds

how people usually look for the MSSM Higgs



- Higgs produced in association with SM particles
- smaller cross section (set by y_b)
- no (BSM) $\not{E}_T$
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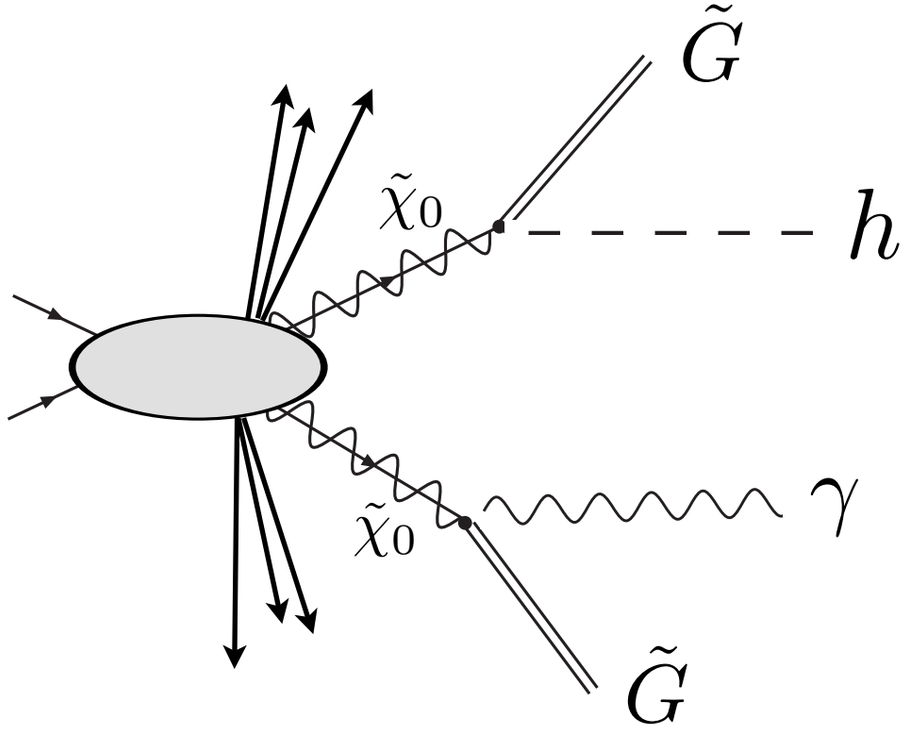

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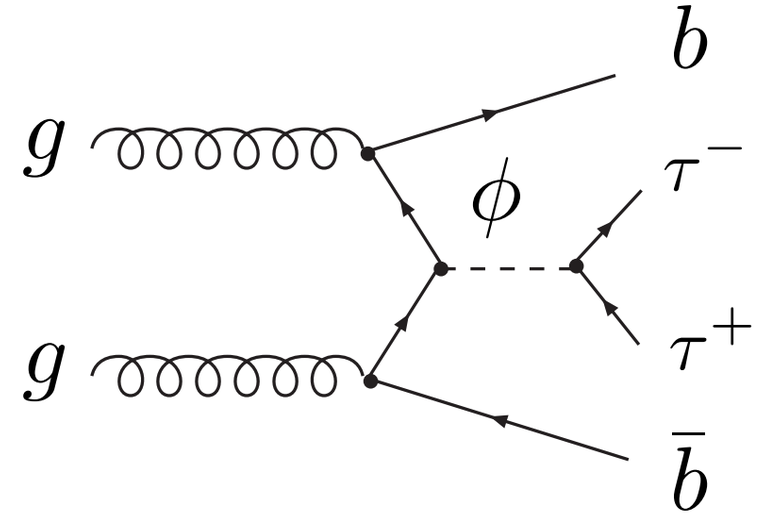

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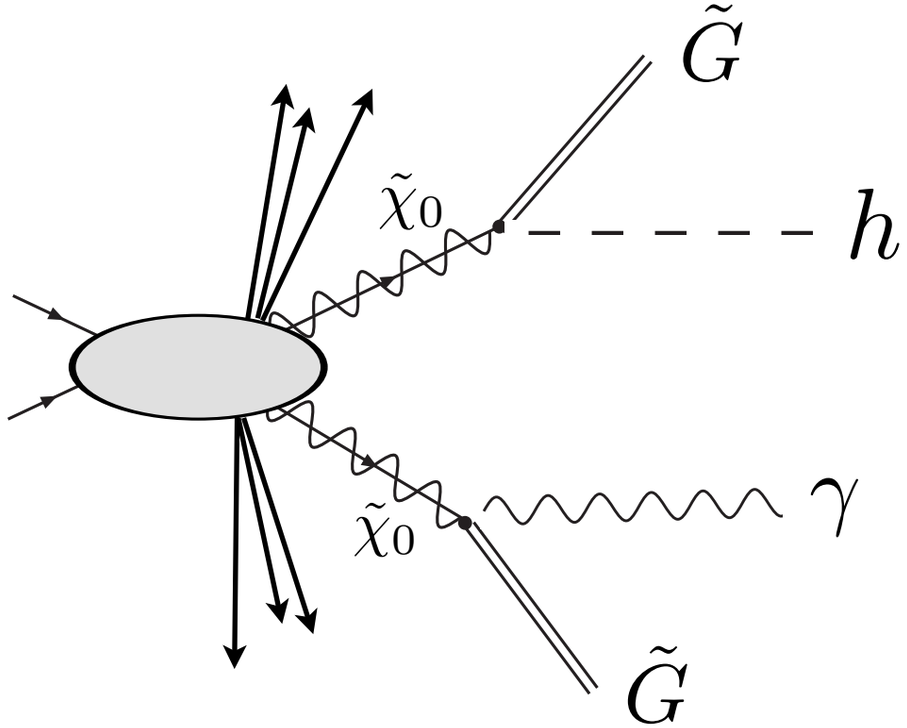
with so much going on in inclusive SUSY events... how can we do better than traditional search ?

Higgses source comparison

how we want to look for the MSSM Higgs



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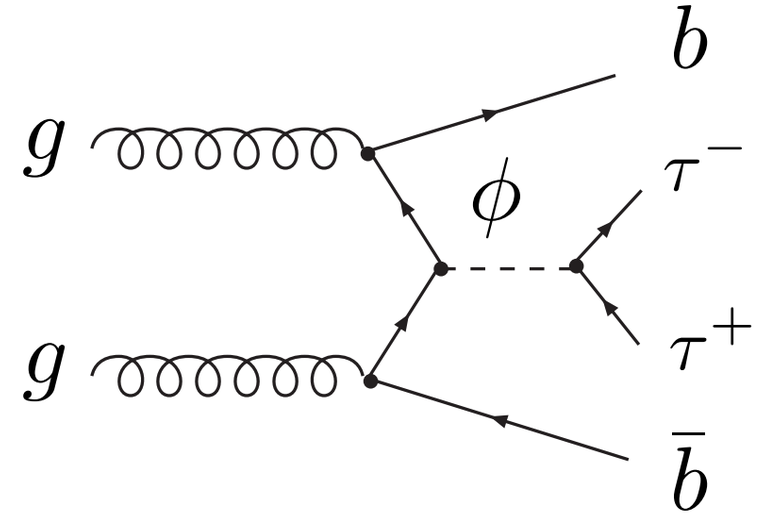

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JET SUBSTRUCTURE!

Remember

* **focus on the subset of new physics events with boosted characteristics**

specifically, demand one or more 'fat' jets: $p_{T,j} > 200 \text{ GeV}$

this limits the kinematic regime, costing us events, but we greatly reduce combinatorial background

* **Our goal is to discover the Higgs, not the new physics!**

* **also, going to high-p_T ⟶ better detector resolution:**

ex., for jets: $\left(\frac{\delta E}{E}\right)_{\text{jets}} \cong \frac{0.6}{\sqrt{E/\text{GeV}}} + 0.03$ (ATLAS TDR, cone jets.)

so boosted analysis are also cleaner

Part II: Jet Substructure Analysis

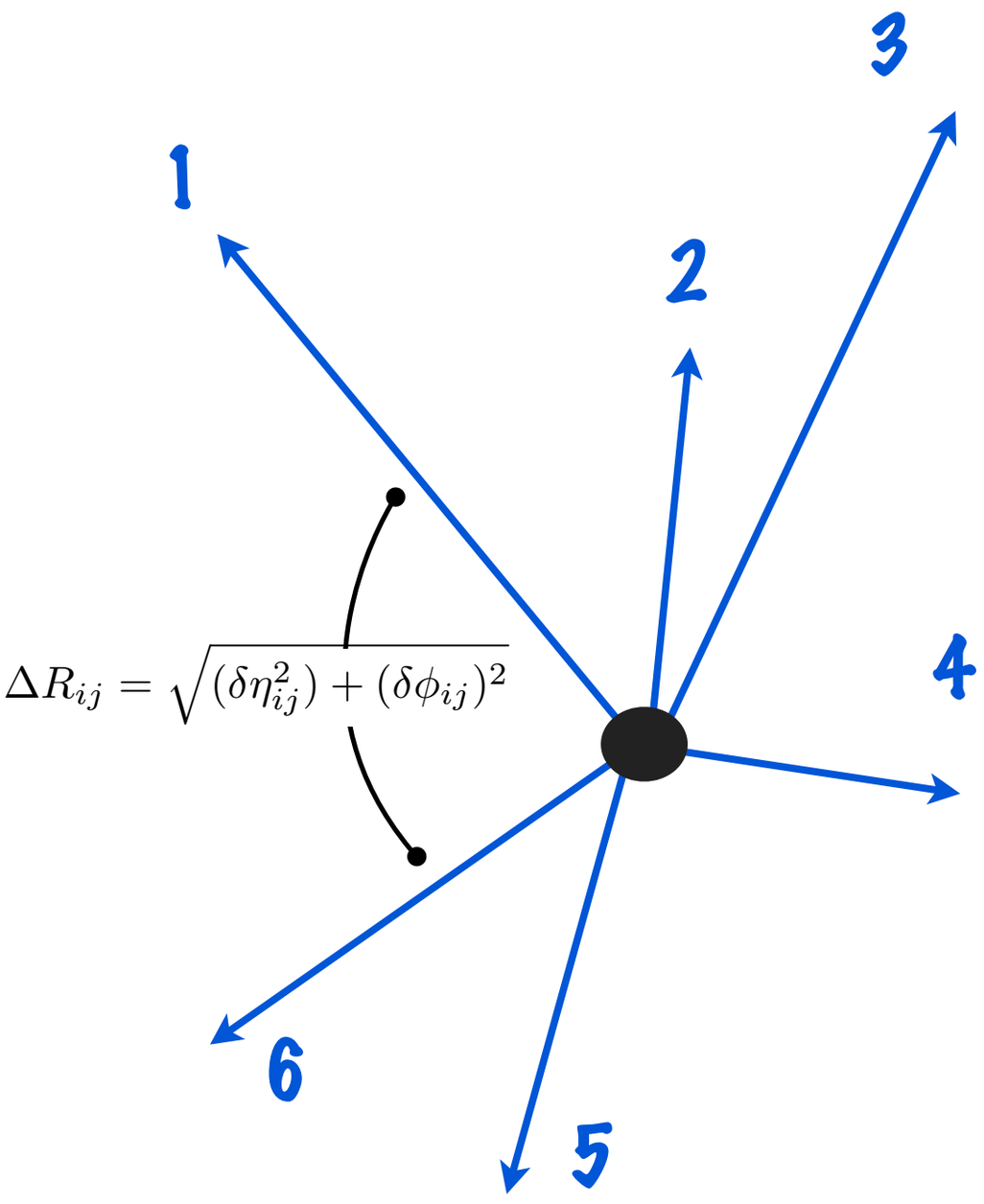
* Combining particles

* Unraveling jets/searching for substructure

* Benefits of substructure

Making and breaking jets

to be able to better use the information contained in jets,
we have to know how they are created



starting from a list of final particles,
calculate:

$$d_{ij} = \min(p_{Ti}^{2n},\, p_{Tj}^{2n})\,\frac{\Delta R_{ij}^2}{R^2}$$

jet 'area'

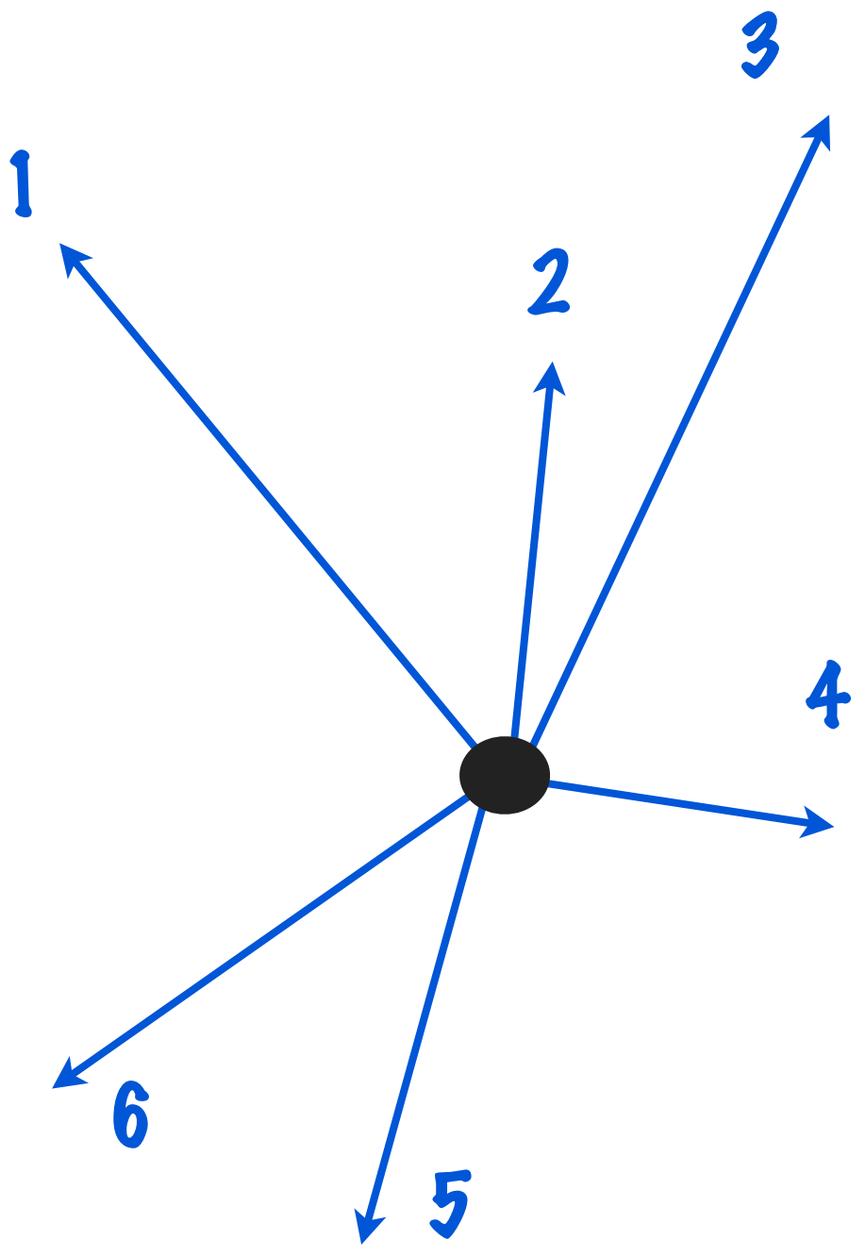
$$d_i = p_{Ti}^{2n}$$

$$n = \begin{cases} n = 1 & k_T \\ n = 0 & \mathrm{C/A} \\ n = -1 & \text{anti-}k_T \end{cases}$$

we use the C/A (angle ordered shower)
throughout

Making and breaking jets

find the minimum: $\min\left(d_{ij}, d_i\right)$

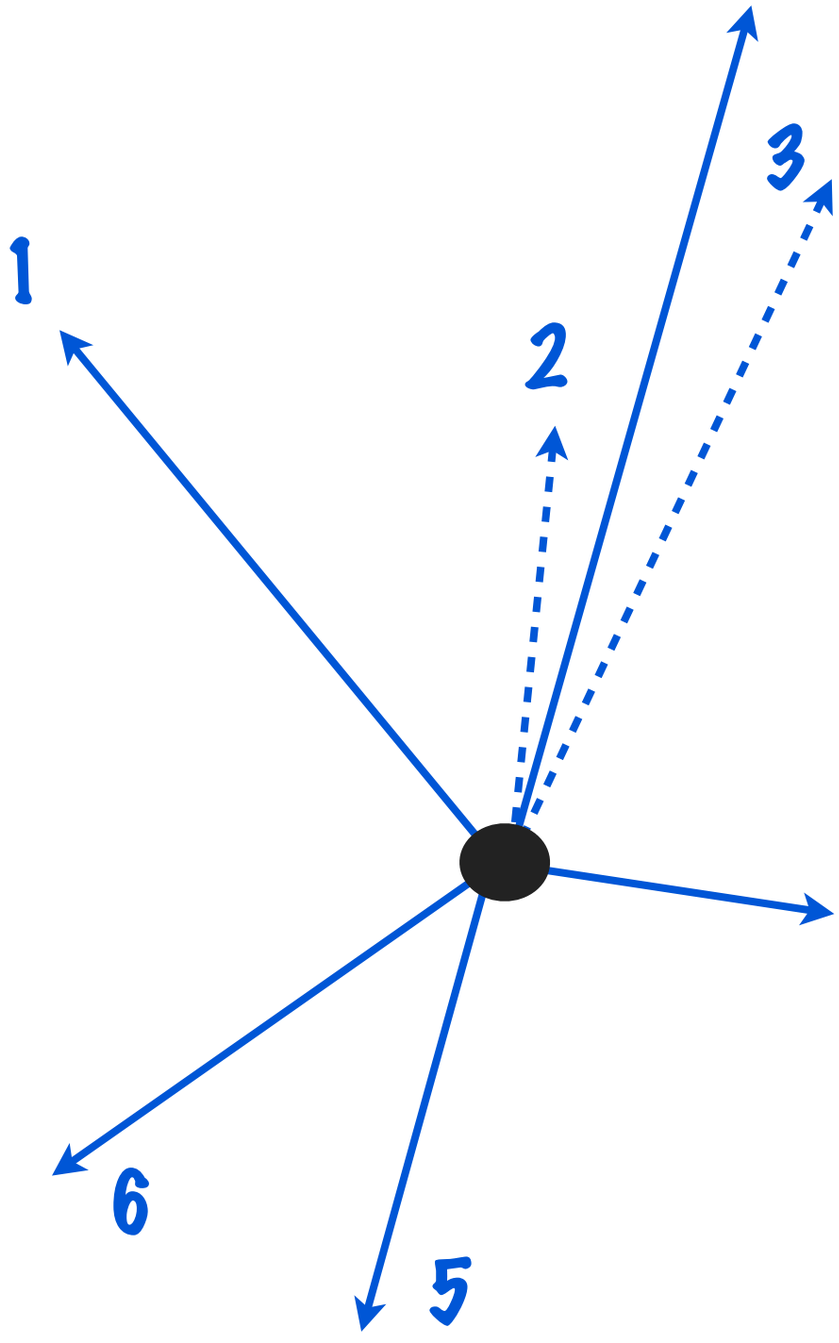


if min is one of the d_{ij} **,**
replace particle_j **and** particle_i
with $\vec{k} = \vec{i} + \vec{j}$

and repeat...

Making and breaking jets

find the minimum: $\min\left(d_{ij}, d_i\right)$



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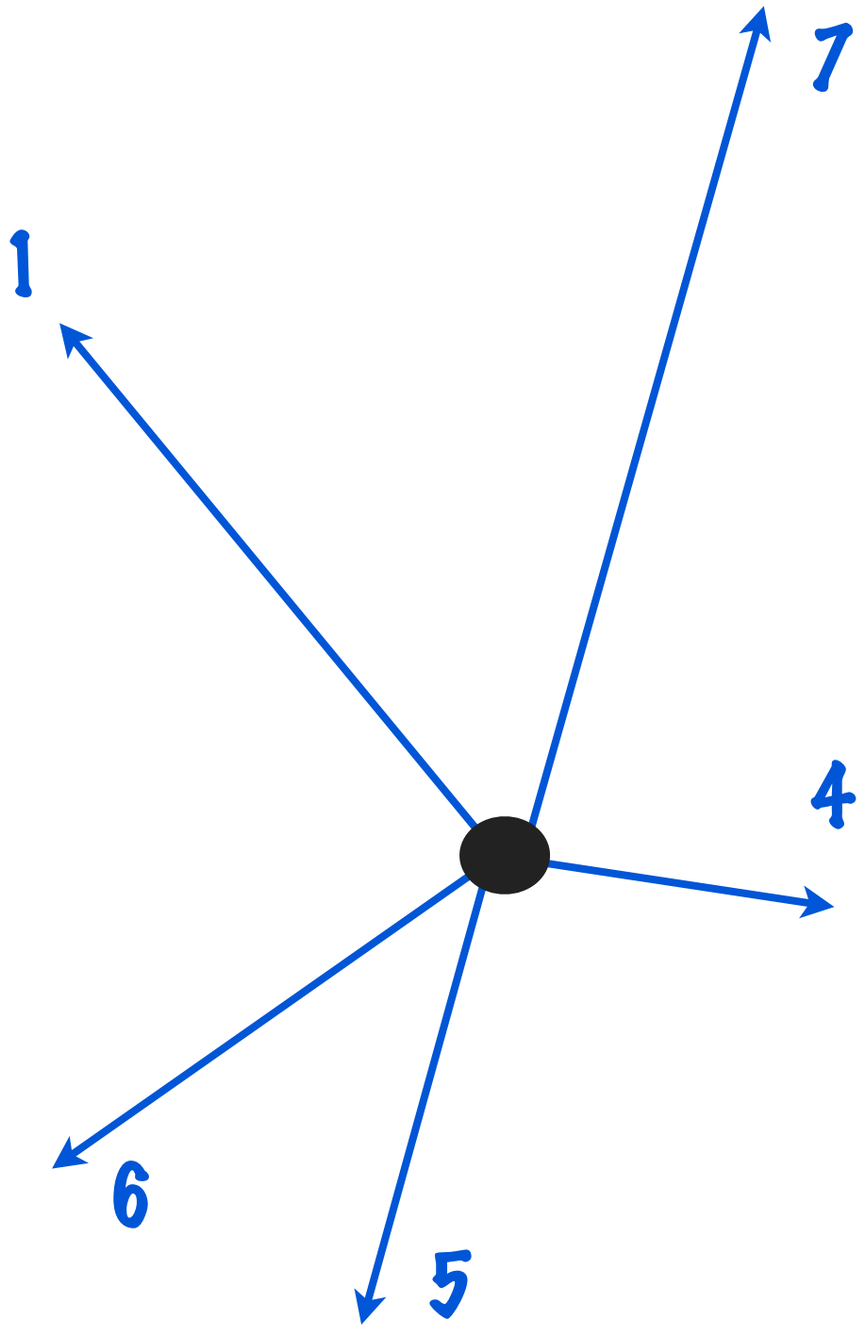

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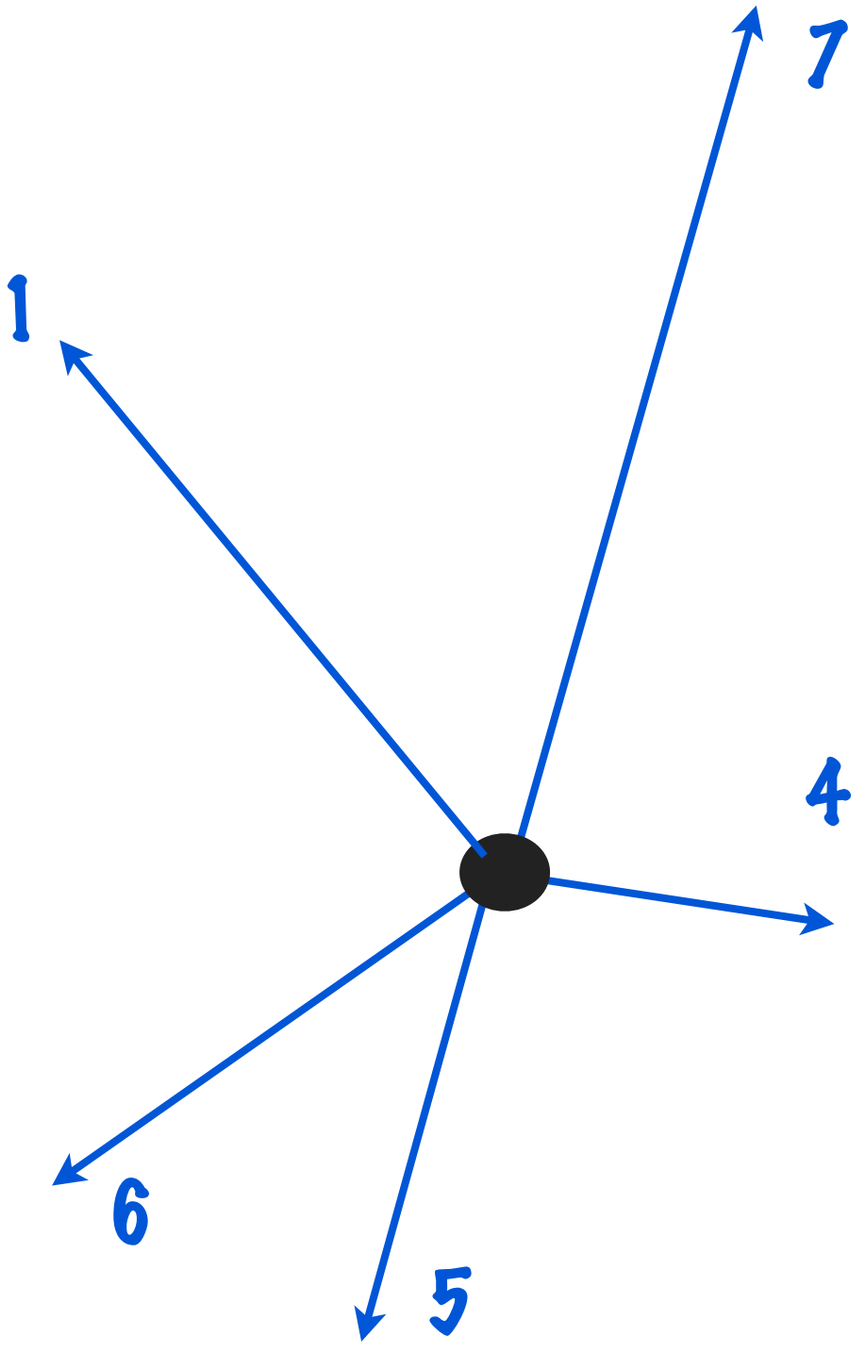
Making and breaking jets

if $\min(d_{ij}, d_i)$ is one of the d_i

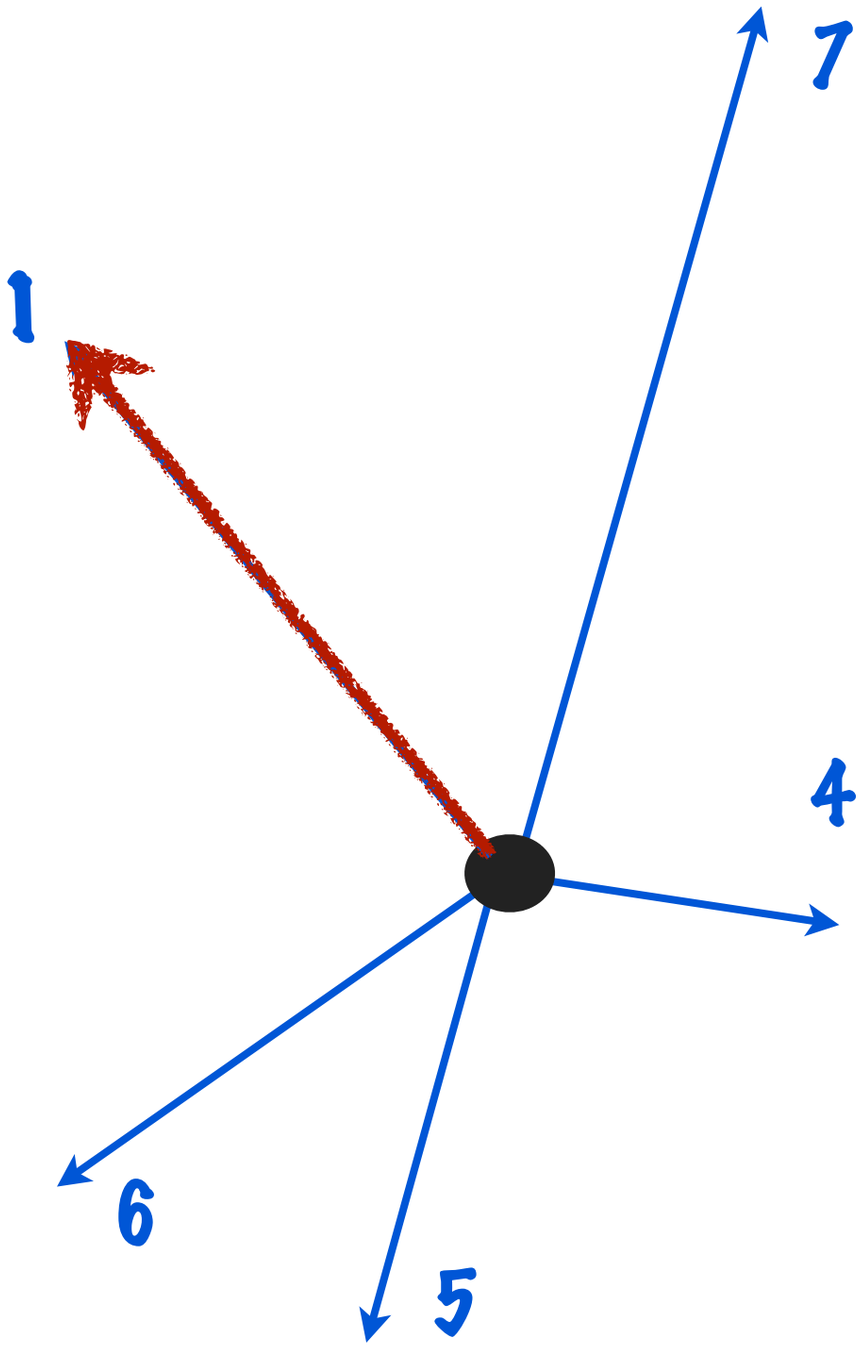


promote $\mathrm{particle}_i$ to a jet,
and remove it from the list

repeat the procedure until the list is empty

Making and breaking jets

if $\min(d_{ij}, d_i)$ is one of the d_i



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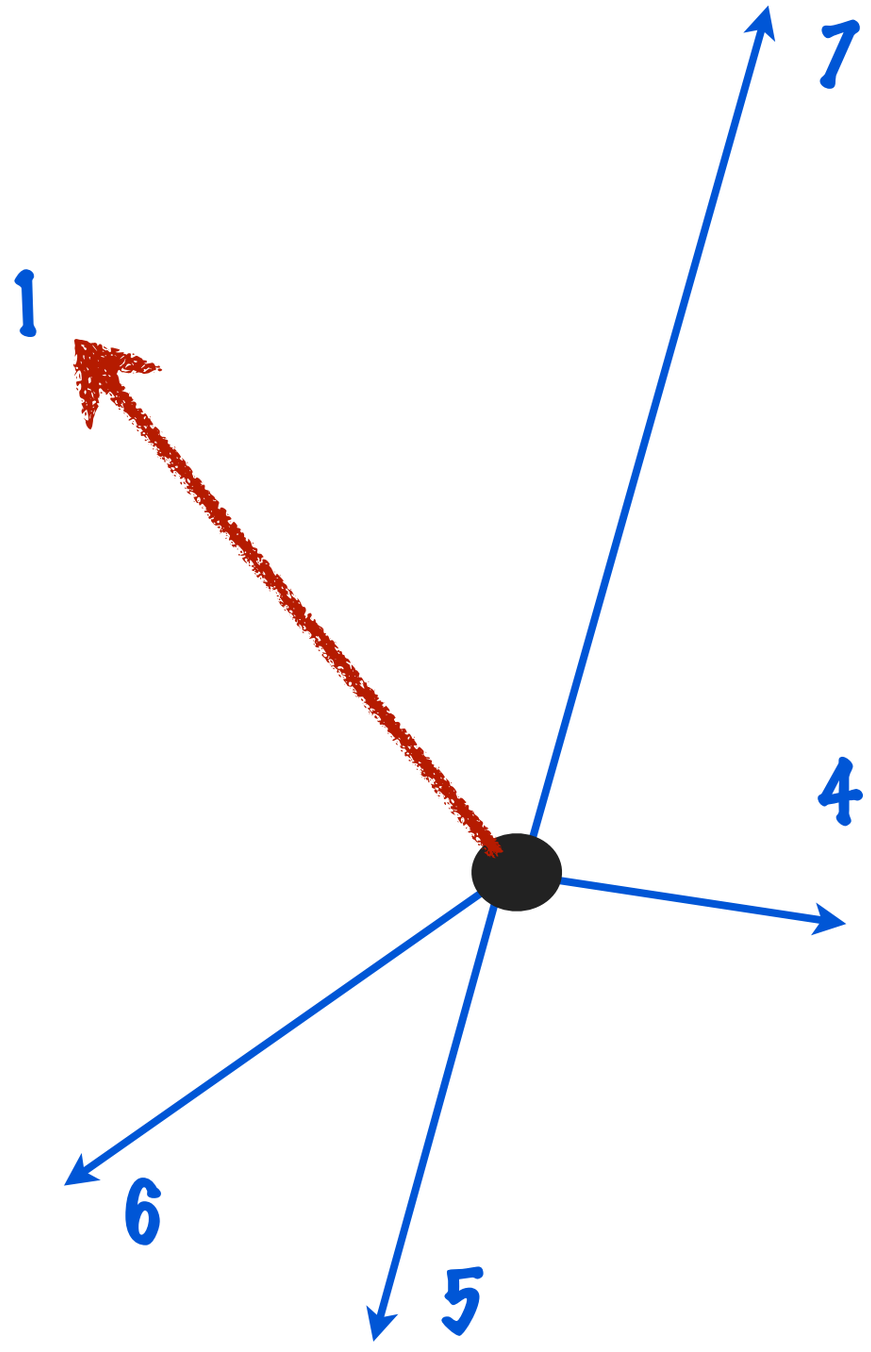

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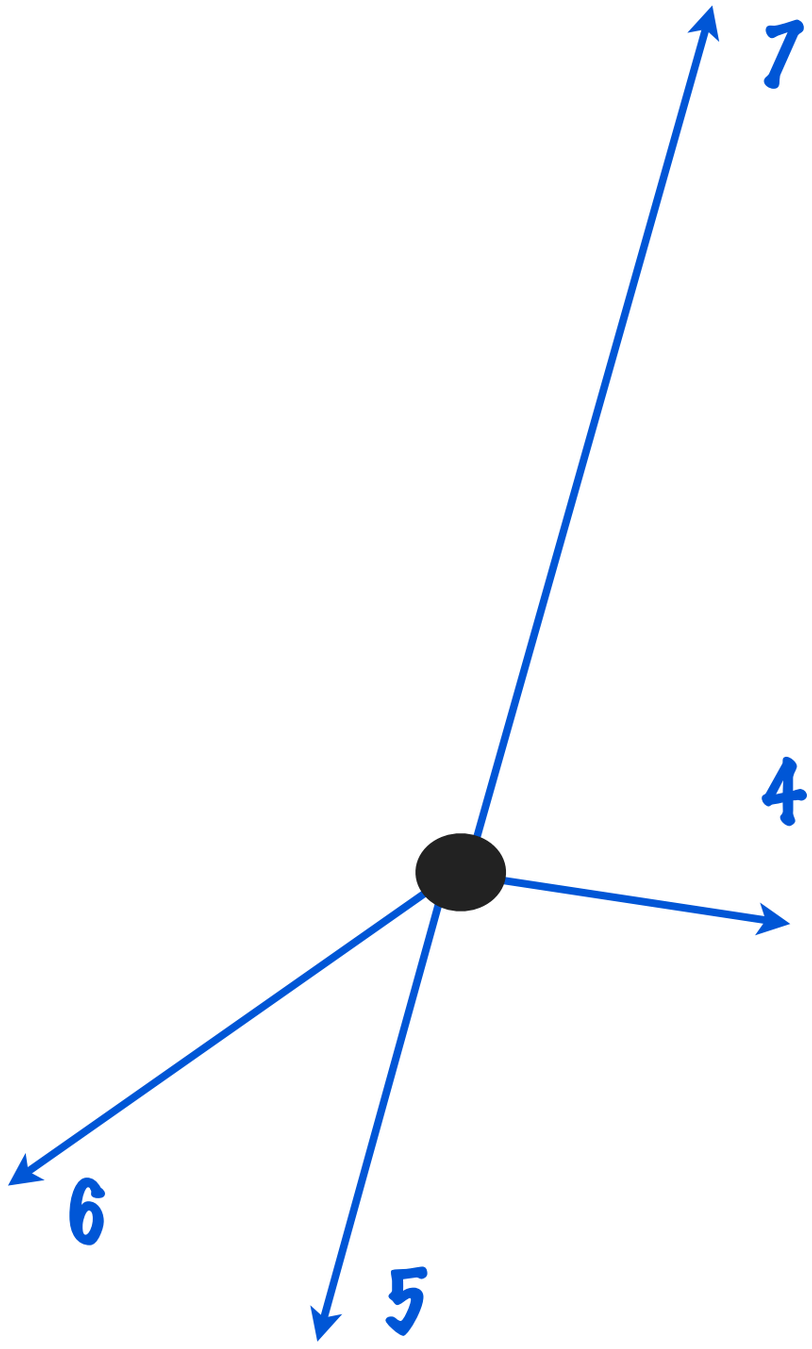

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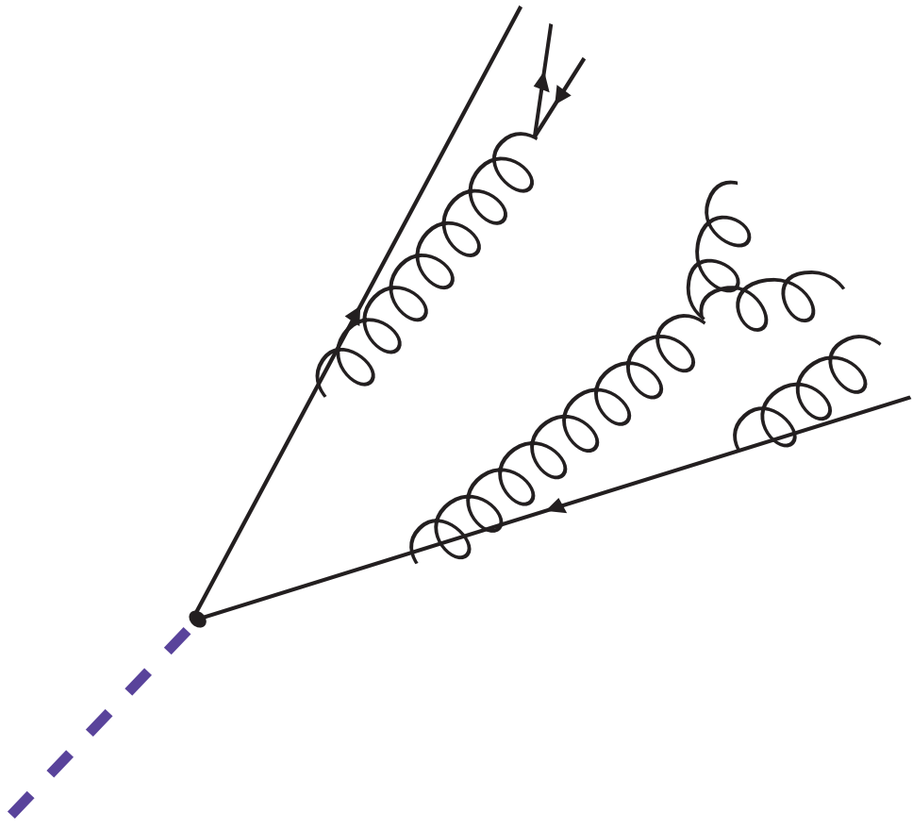
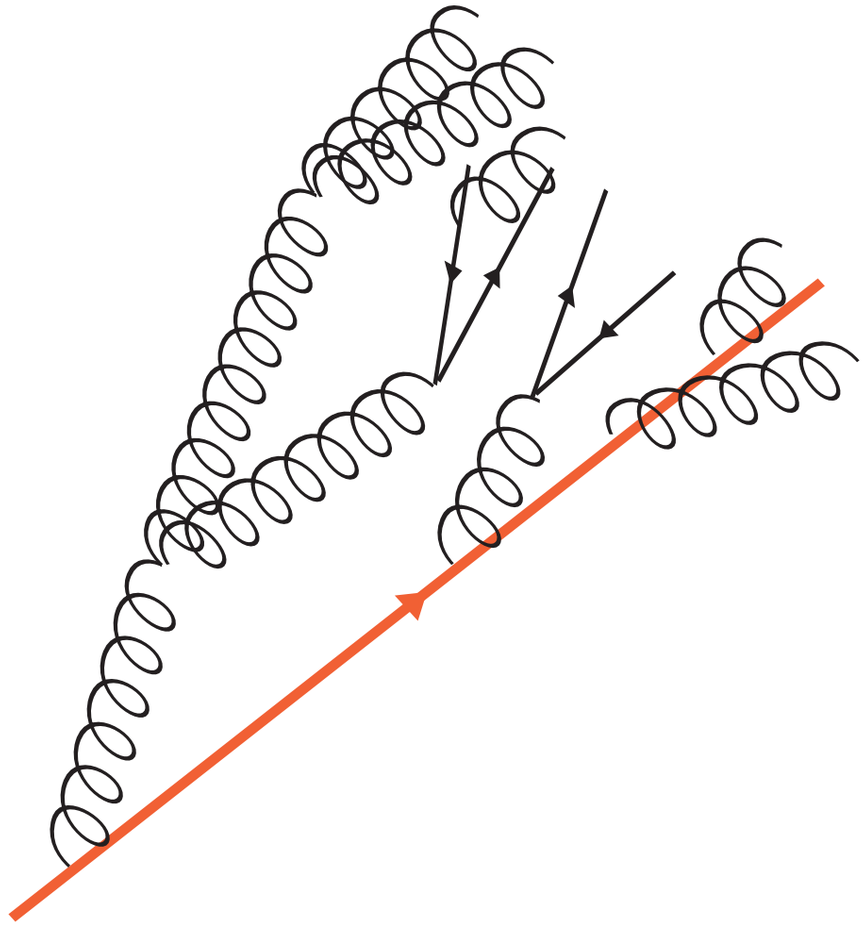
Jet Substructure #1

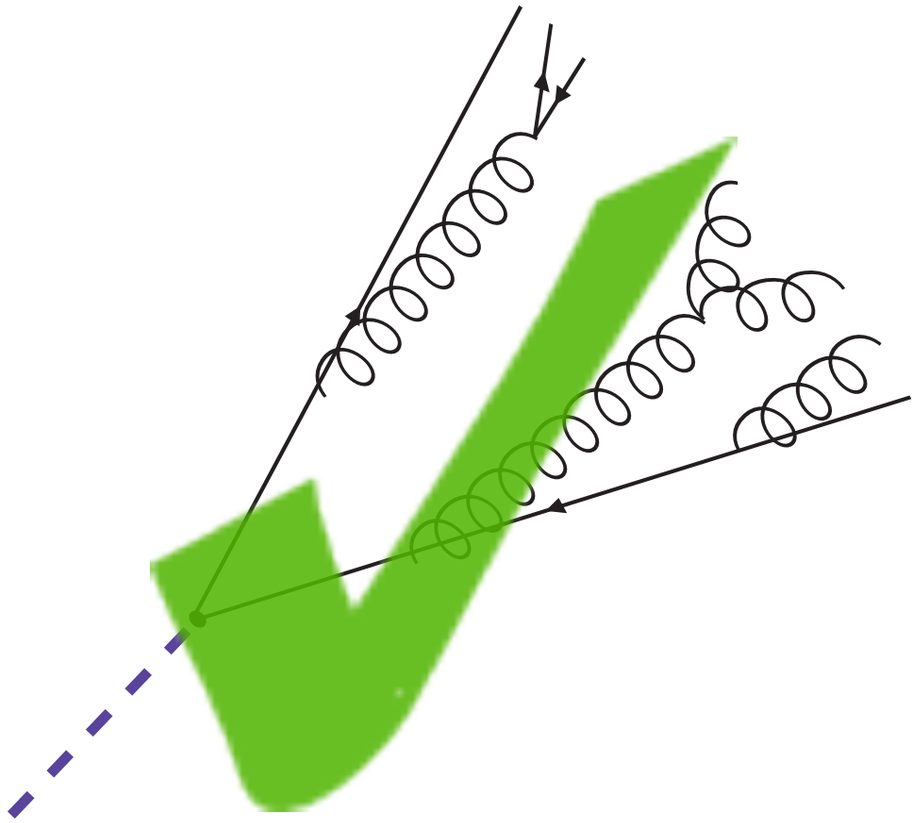
The goal is to separate jets with a heavy particle decay from those without

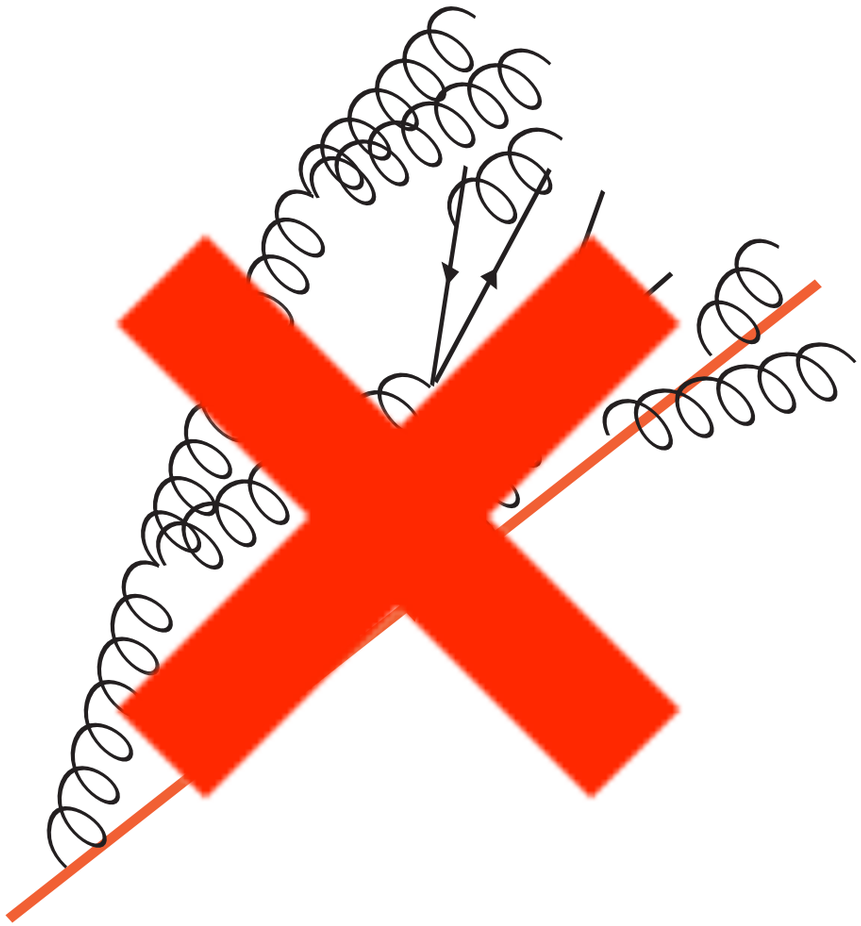




Jet Substructure #1

The goal is to separate jets with a heavy particle decay from those without



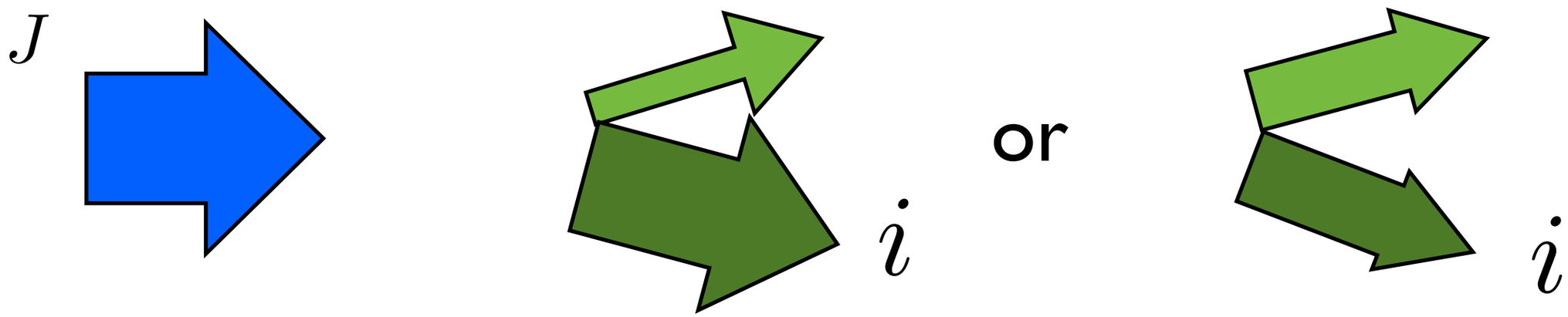


Jet Substructure #2

(Butterworth et al 0802.2470)

For each jet ($R = 1.2$) in the event:

1. Undo the last stage of clustering $J \to i + j$, calling the more massive daughter i .



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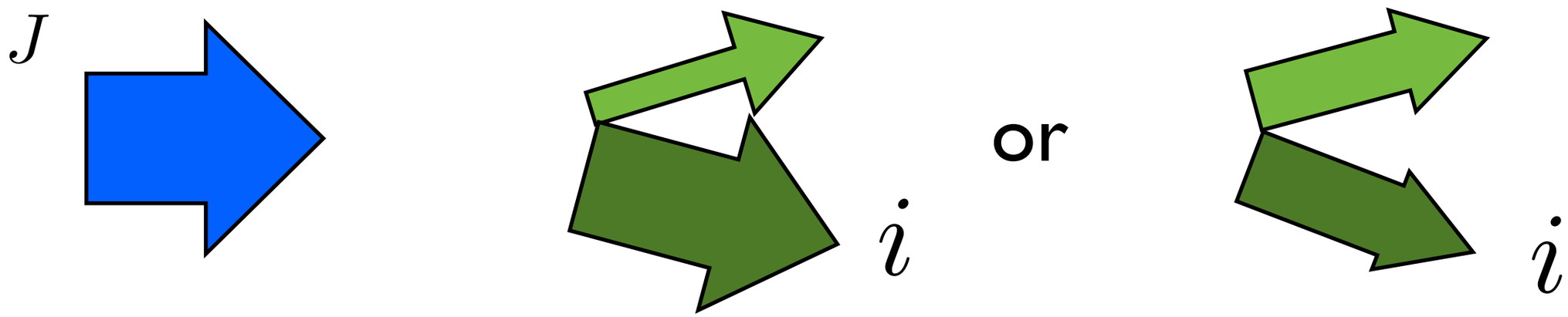

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so only keep events with **significant mass-drop:** $m_i < \mu\, m_J$

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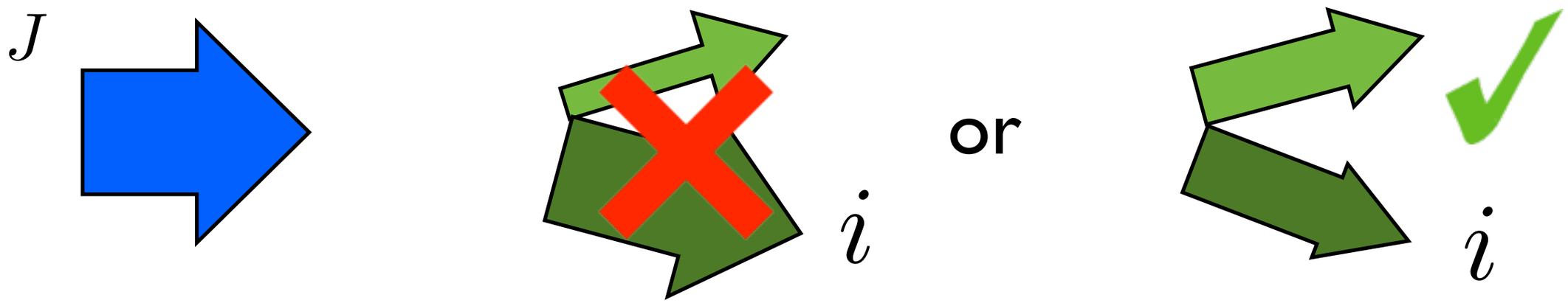

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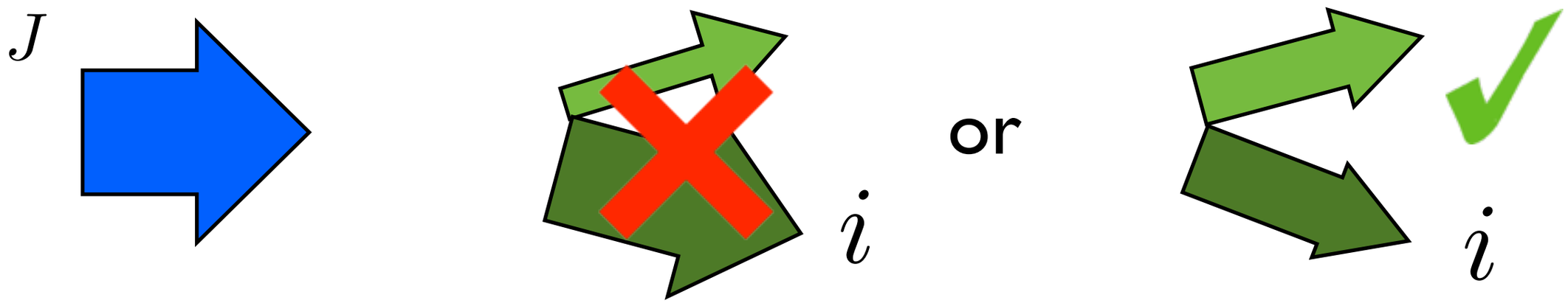

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But rates for QCD jets/BSM jets are so high, we need another handle:

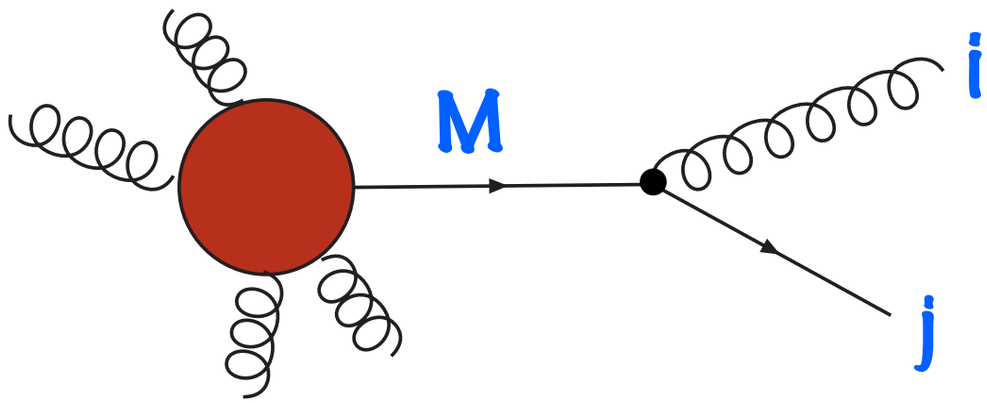
demand: $\dfrac{\min(p_{T_i}^2, p_{T_j}^2)}{m_J^2} \Delta R_{ij}^2 \; > (0.3)^2$

Jet Substructure #3

for massless daughter particles:

$$\frac{\min(p_{T_i}^2, p_{T_j}^2)}{m_J^2}\Delta R_{ij}^2 \longrightarrow \frac{\min(E_i, E_j)}{E_J} \equiv z$$

... in soft, collinear limit

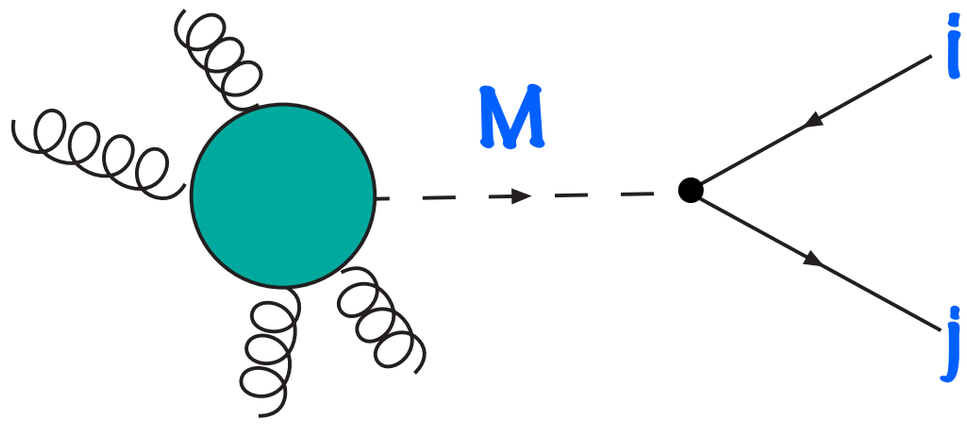


$$df_{M\to ij}^{QCD} \sim dQ_M^2 dz \frac{1}{Q_M^2} P_{M\to ij}(z)$$

blows up as $z \to 0$

$$df_{M\to ij}^{res} \sim dQ_M^2 dz \frac{\Gamma_{M\to ij}}{\Gamma_{M,tot}} \delta(Q_M^2 - m_{res}^2)$$

nonsingular in z



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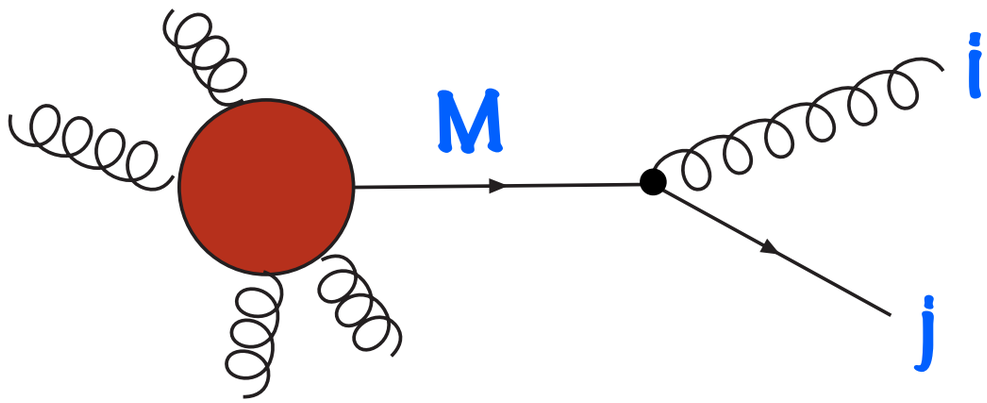

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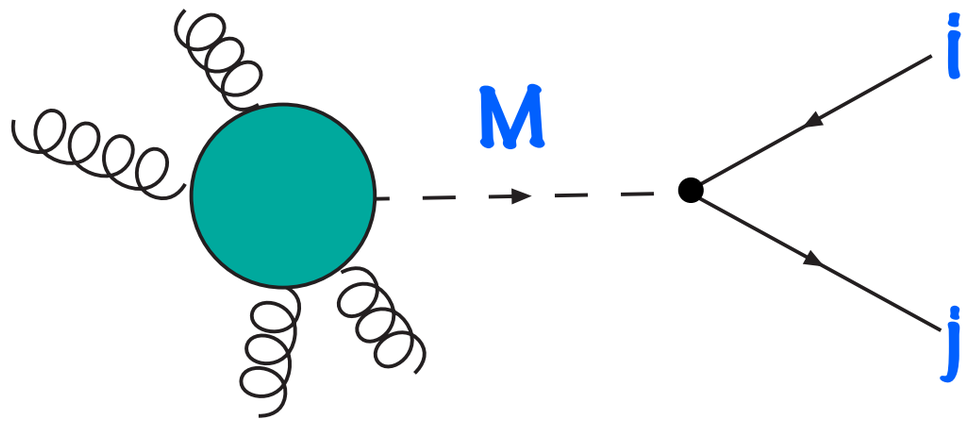
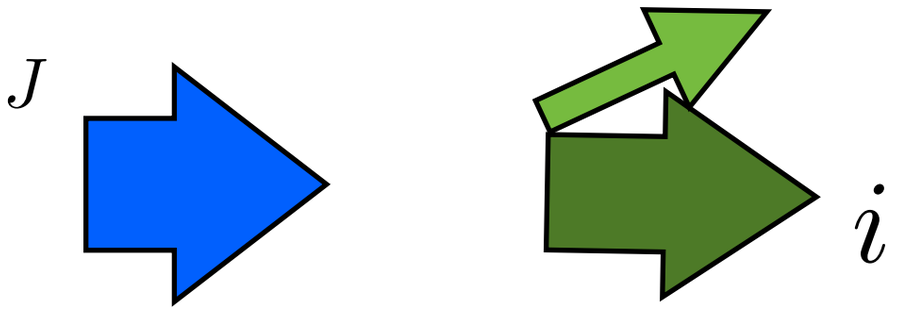


cut $\frac{\min(p_{T_i}^2, p_{T_j}^2)}{m_J^2}\Delta R_{ij}^2 > (0.3)^2$ **suppresses QCD contamination**

Jet Substructure #4

2. If conditions not met, continue unclustering using more massive daughter jet as new parent



BUT if both conditions met, stop unclustering

Identity ΔR_{ij} as the substructure scale R_{sub}

3. For jets with substructure, resolve at scale $\cong R_{sub}/2$

this captures the perturbative, angle-ordered radiation associated with the subjets, while filtering out diffuse radiation like the underlying event

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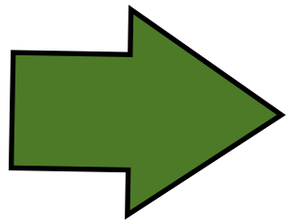

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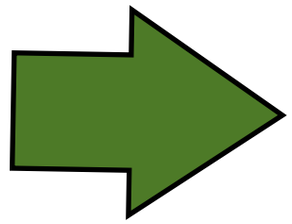

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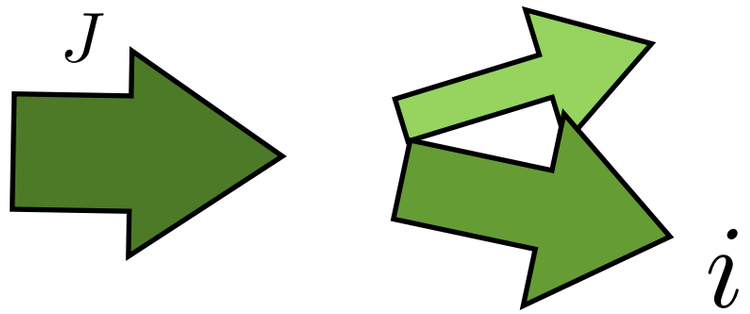

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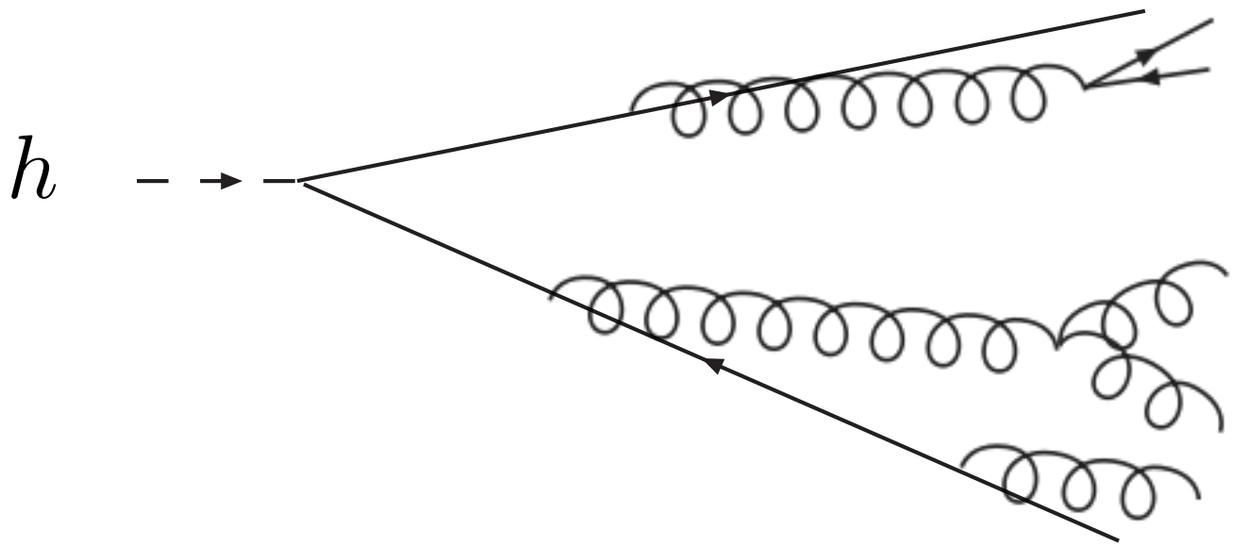

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if two of the three hardest subjets are tagged as b-jets :

candidate Higgs

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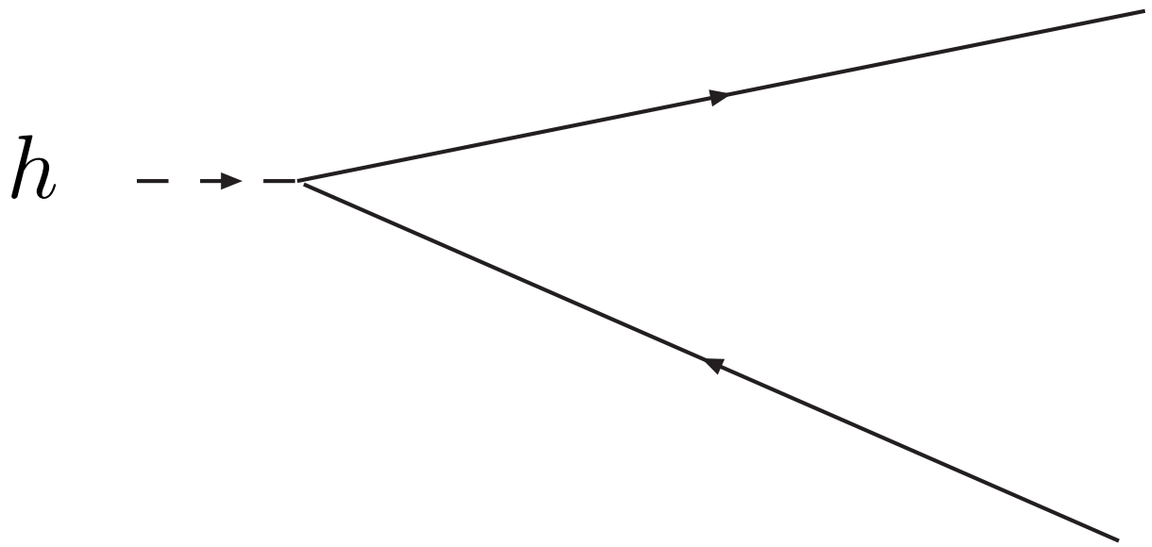

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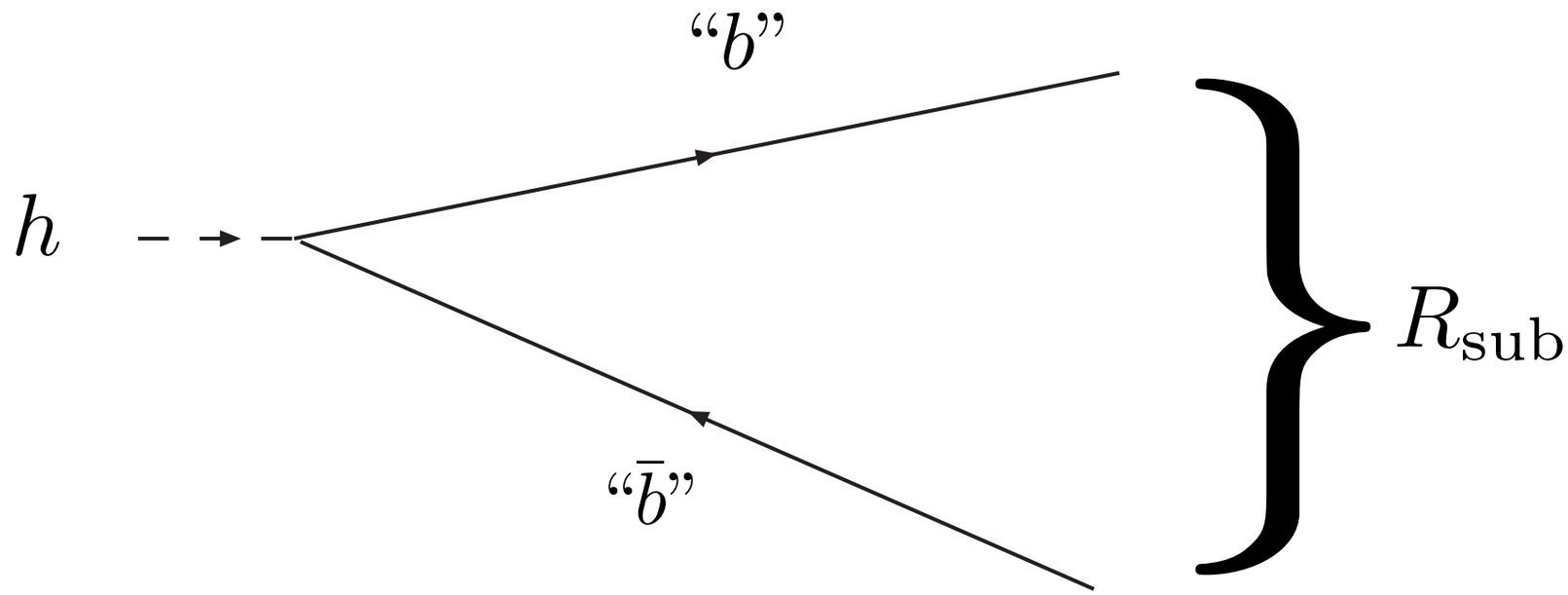

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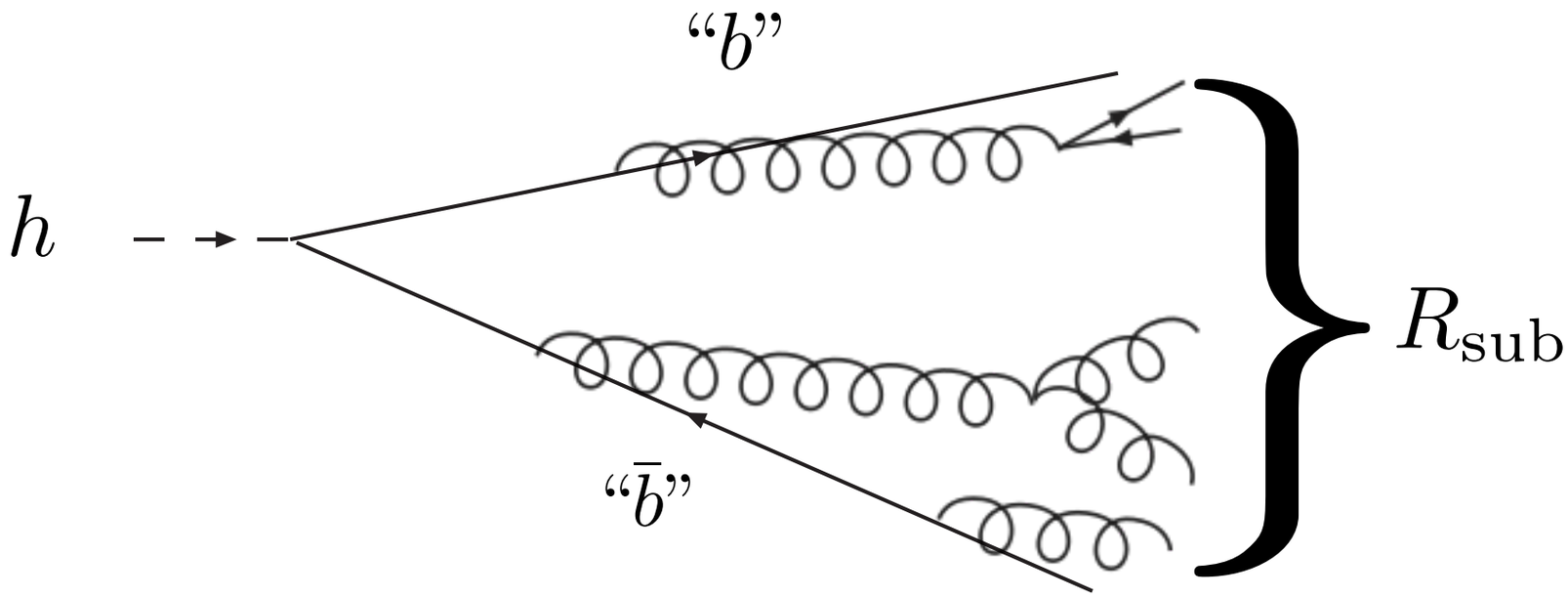

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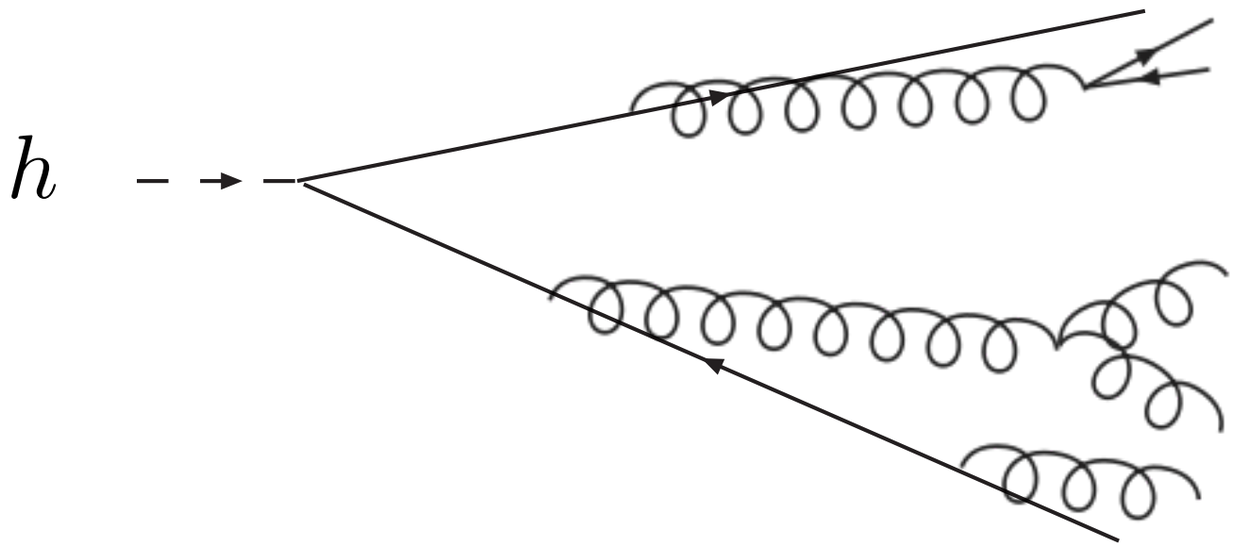

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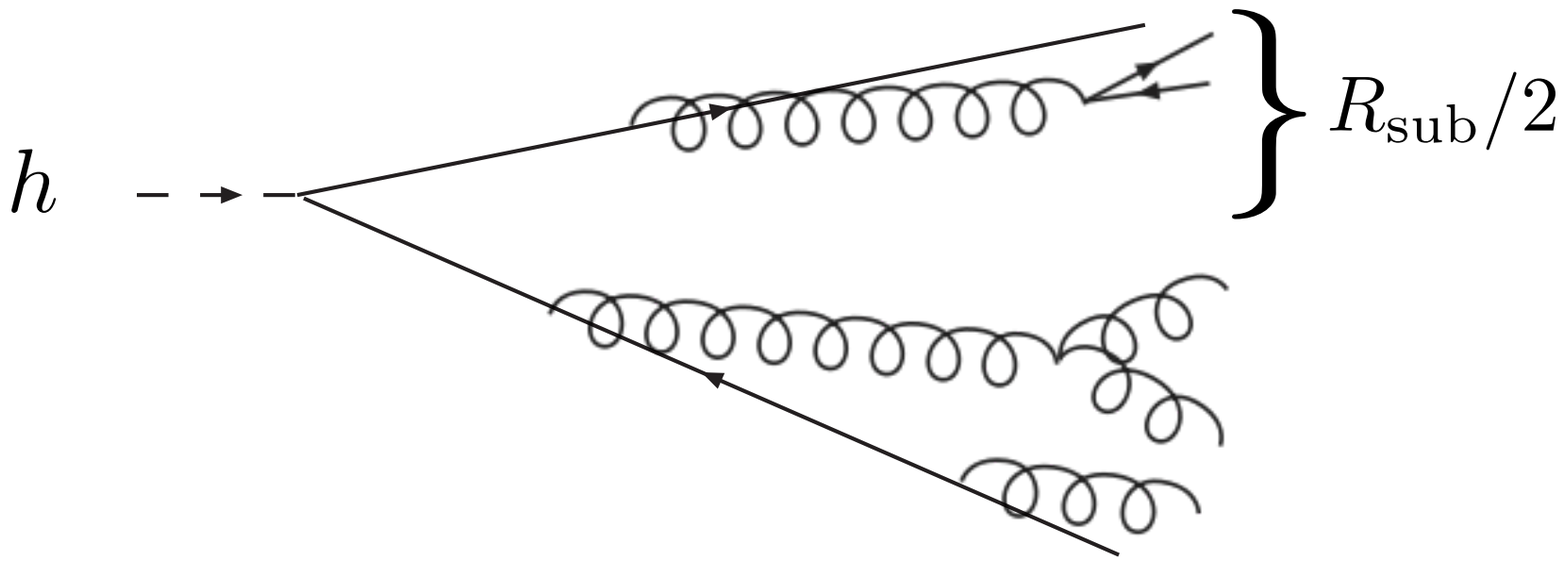

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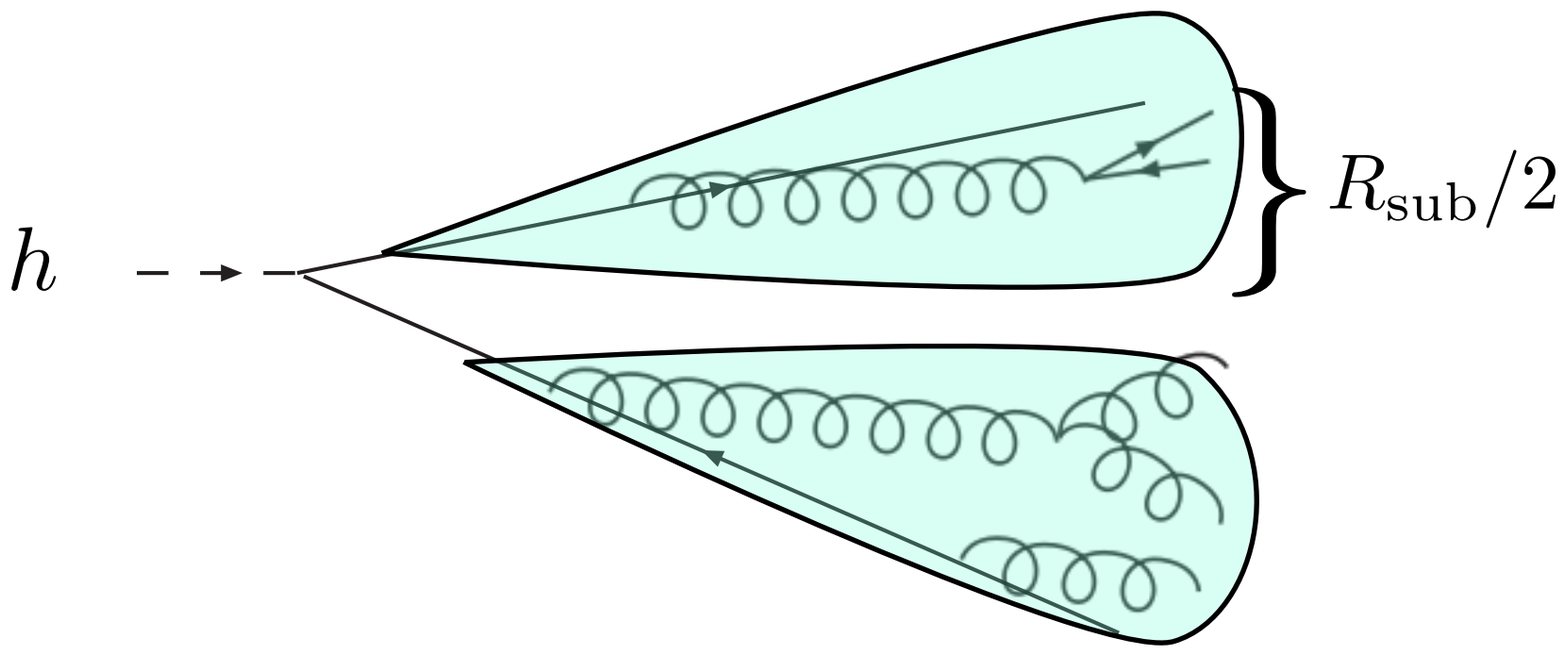

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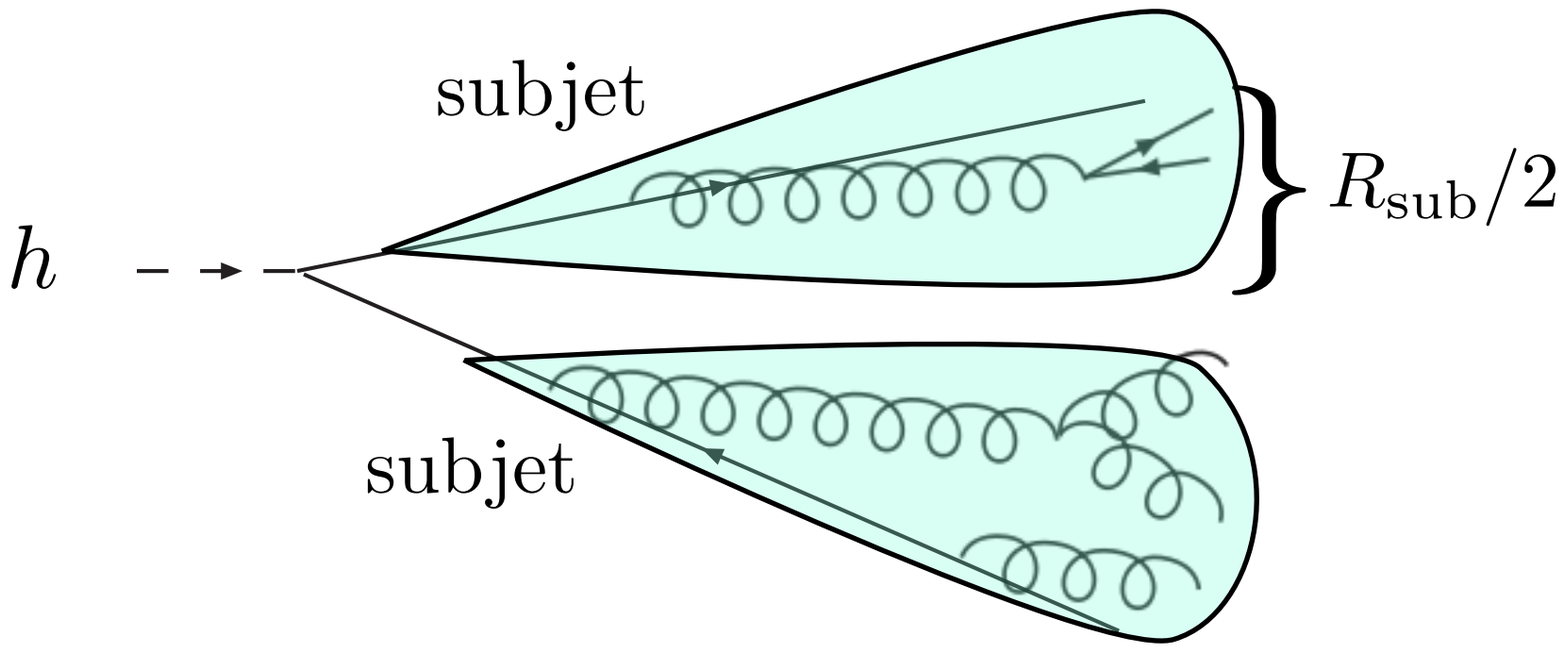

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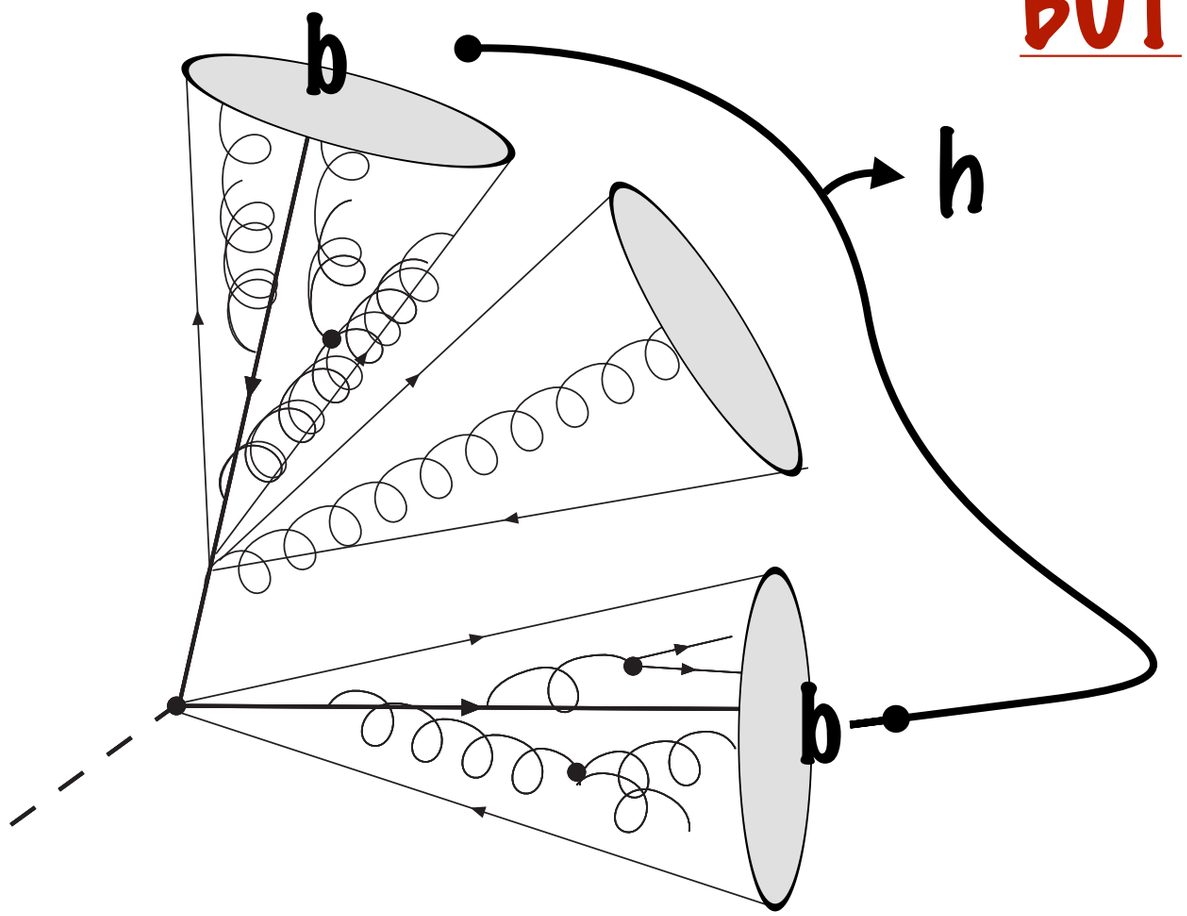
Why substructure?

- Seems like we are doing a lot of work.
  Isn't there an easier way, such as:

Why not just start with a smaller cone?



BUT

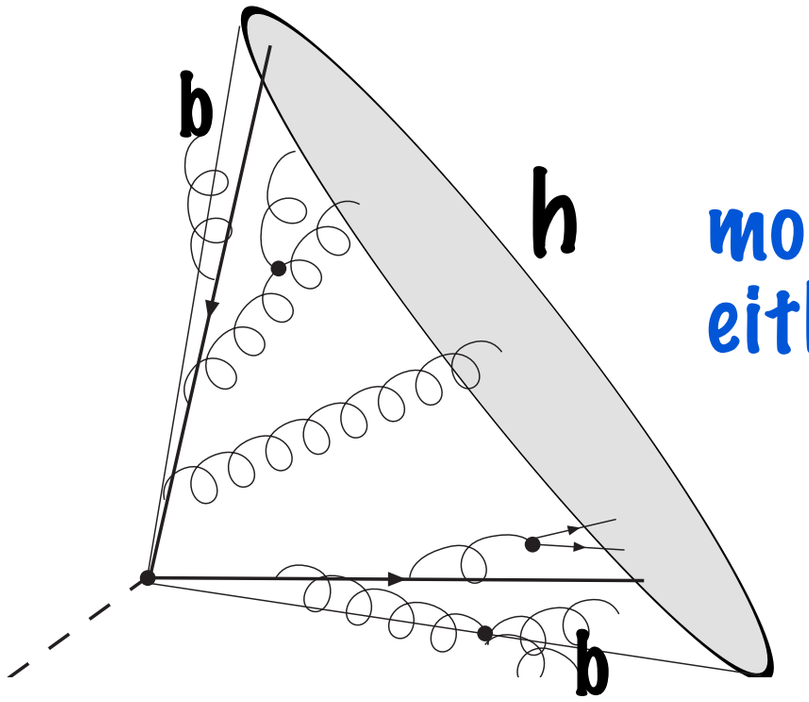
QCD radiated jets can carry much of the 'mother' particle's mass...

Small cones miss this mass, degrading the jj invariant mass resolution

(Seymour, '94)

Why substructure?

Why not a big cone, with multiple b tags?



the bigger the cone, the more extraneous jets we allow in, either from radiation/underlying event

... leading to worse resolution on m_{jj}

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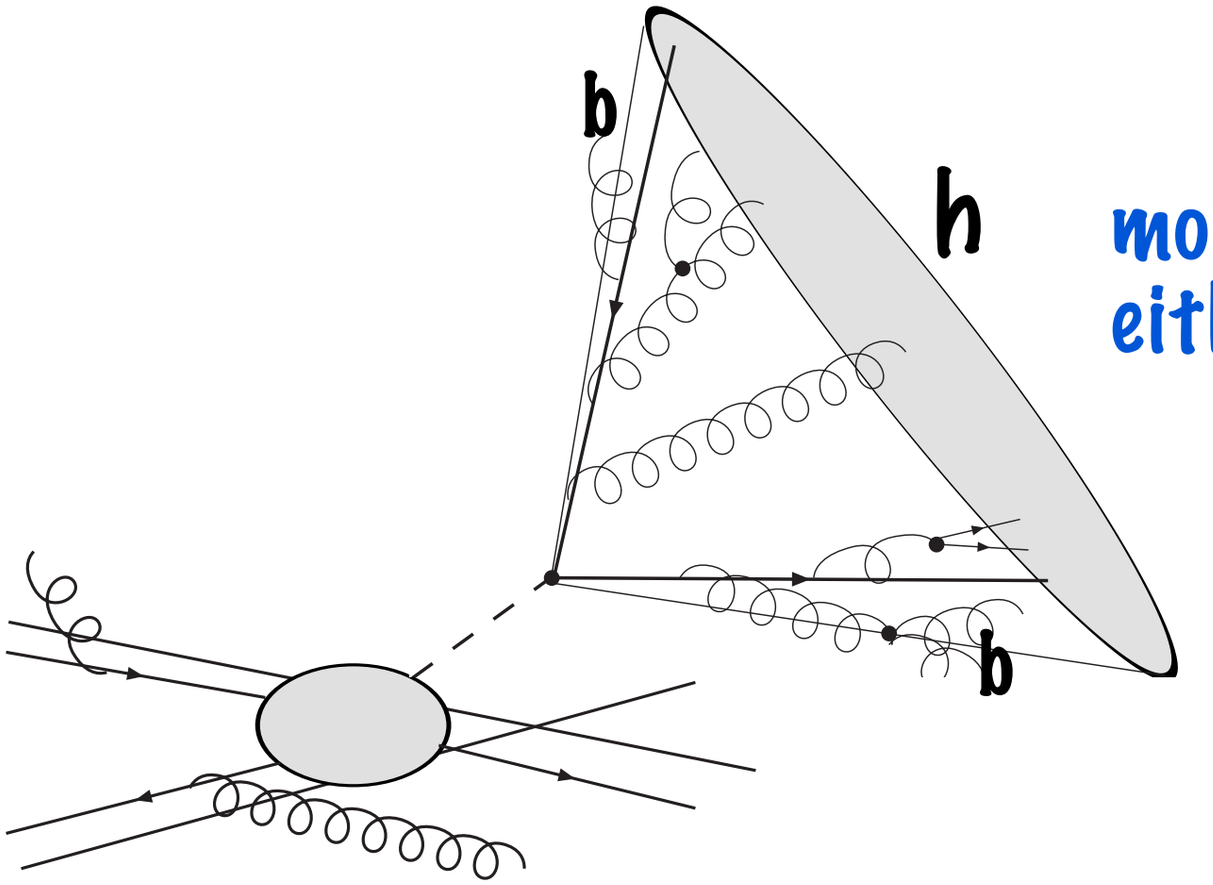

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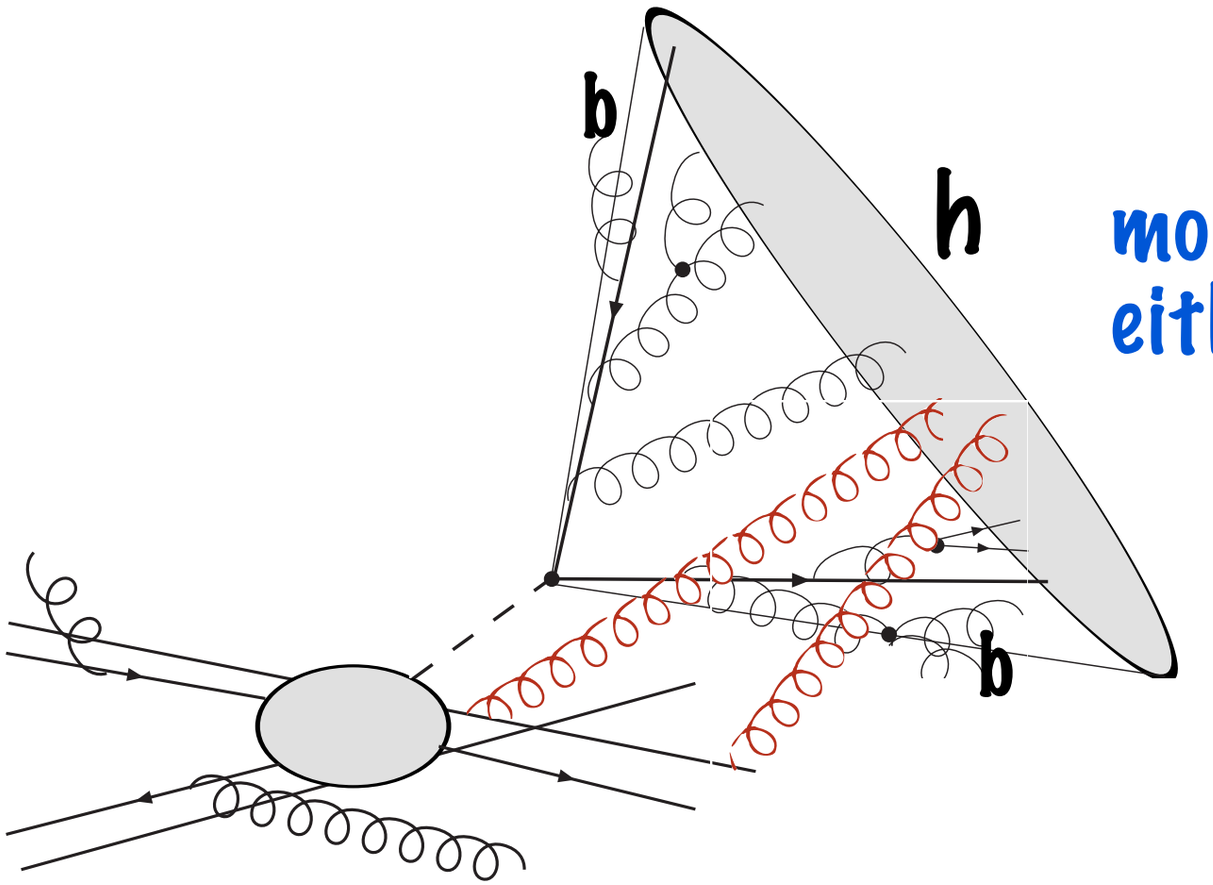

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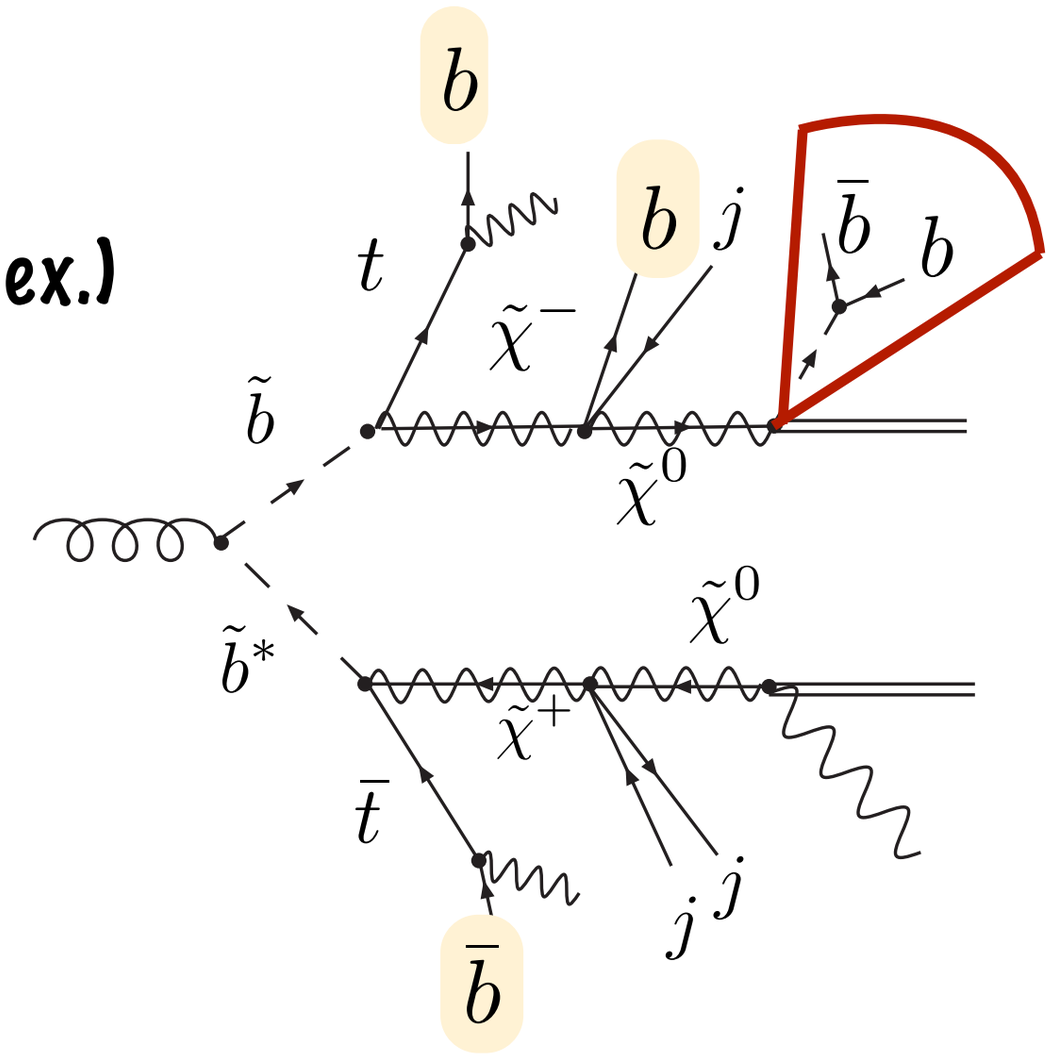
Improved jet substructure

The large number of b quarks, especially when 3rd generation squarks are important in SUSY production, becomes a problem (similar to t-tbar-h in SM)

(Plehn, Salam, Spannowsky '09)

ex.)



extra b's can end up in the 'higgs jet' disrupting the substructure algorithm

identifying a pair of heavy particles is no longer enough

Improved jet substructure

- add another handle: p_T similarity

rather than stop at a mass drop, calculate

$$S_i = \frac{\min(p^2_{T_{j1}}, p^2_{T_{j2}})}{(p_{T_{j1}} + p_{T_{j2}})^2} \Delta R_{j_1 j_2}$$

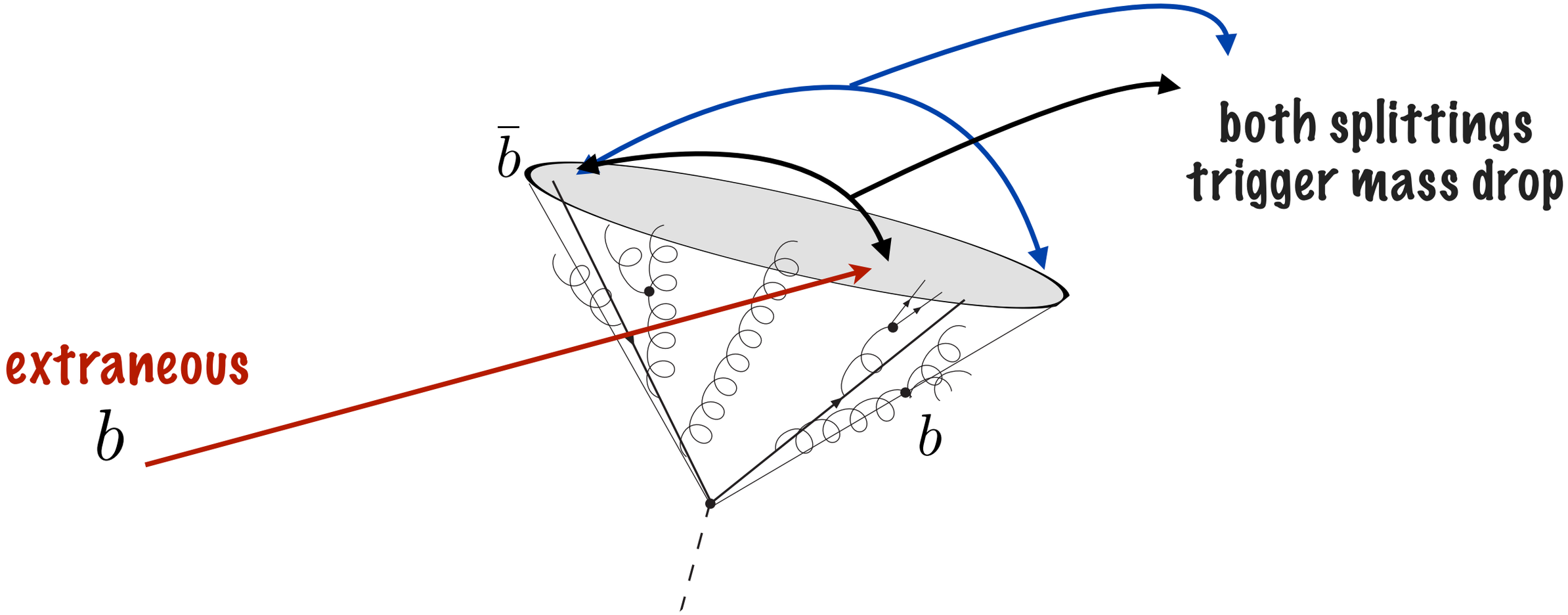
and continue undoing the original jet

at each subsequent mass drop, record S_i

(Kribs, AM, Roy, Spannowsky)

Improved jet substructure

- Identify the splitting with maximum S_i and two daughter b-jets as the Higgs candidate



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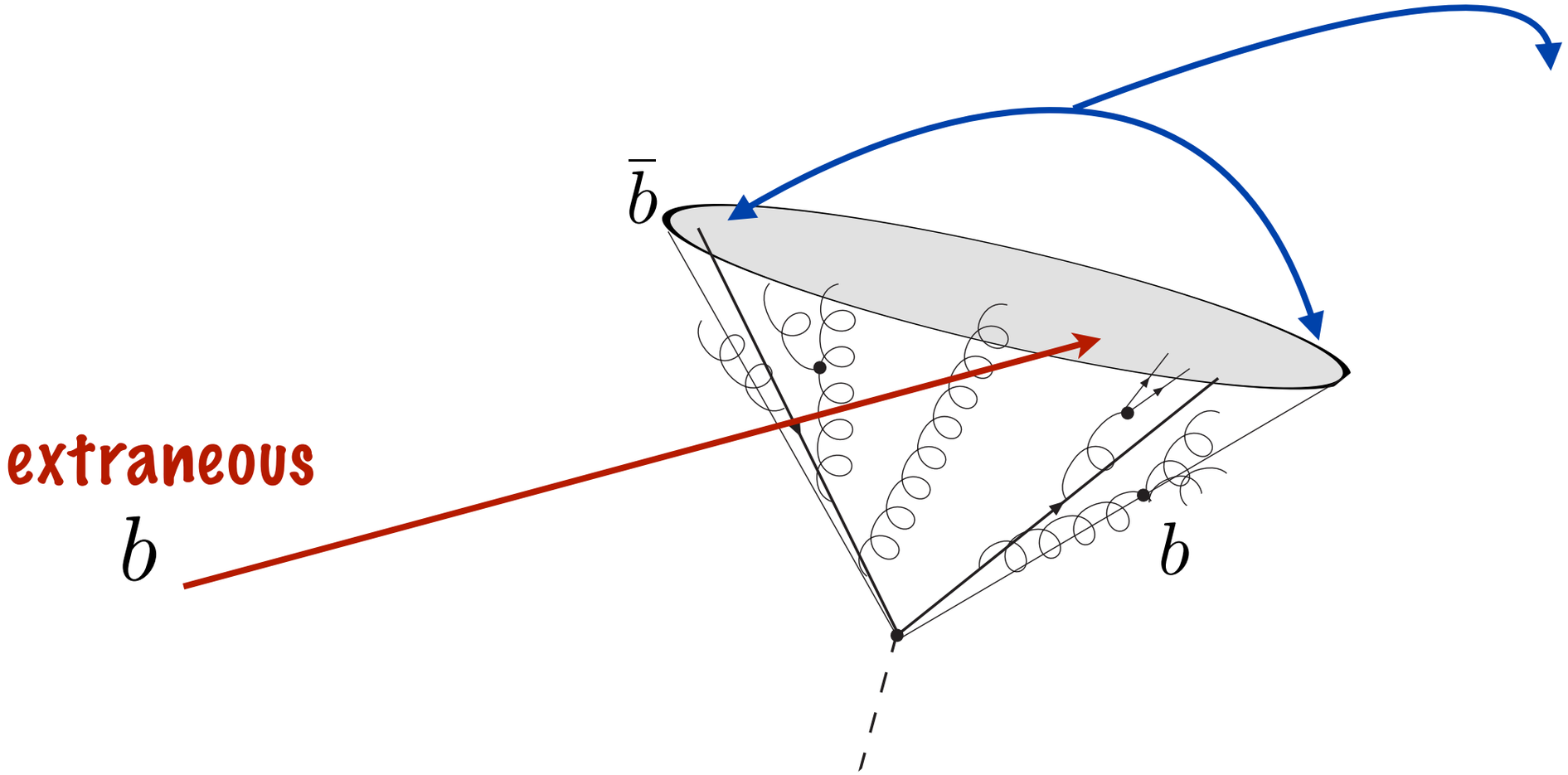

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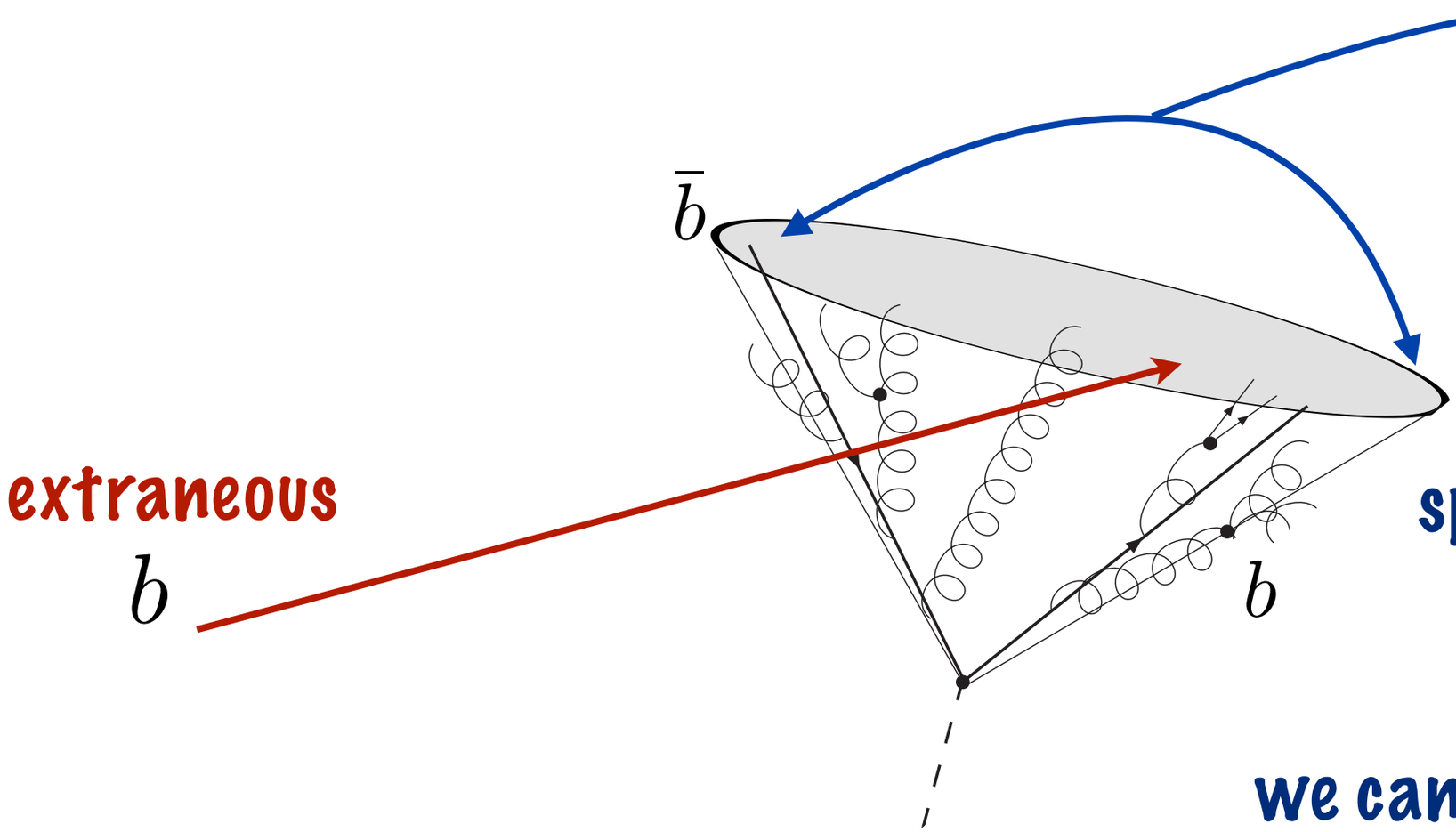


but

by selecting the splitting with the more even distribution of subjet p_T

we can reduce contamination

Improved Jet Substructure on BSM:

1. cluster particles into jets, $R = 1.2$

2. for each fat jet, undo clustering step by step, looking for mass drop and even splitting of energy between daughters.

   If conditions met, record $\Delta R_{sub,i}$ and S_i. Keep unclustering until no more parent jets

3. Determine which splitting n has most even p_T splitting

4. Resolve the fat jet into subjets at the scale $\cong \Delta R_{sub,n}/2$

5. if two of the three hardest subjets are tagged as b-jets

   → candidate Higgs jet ←

Part III

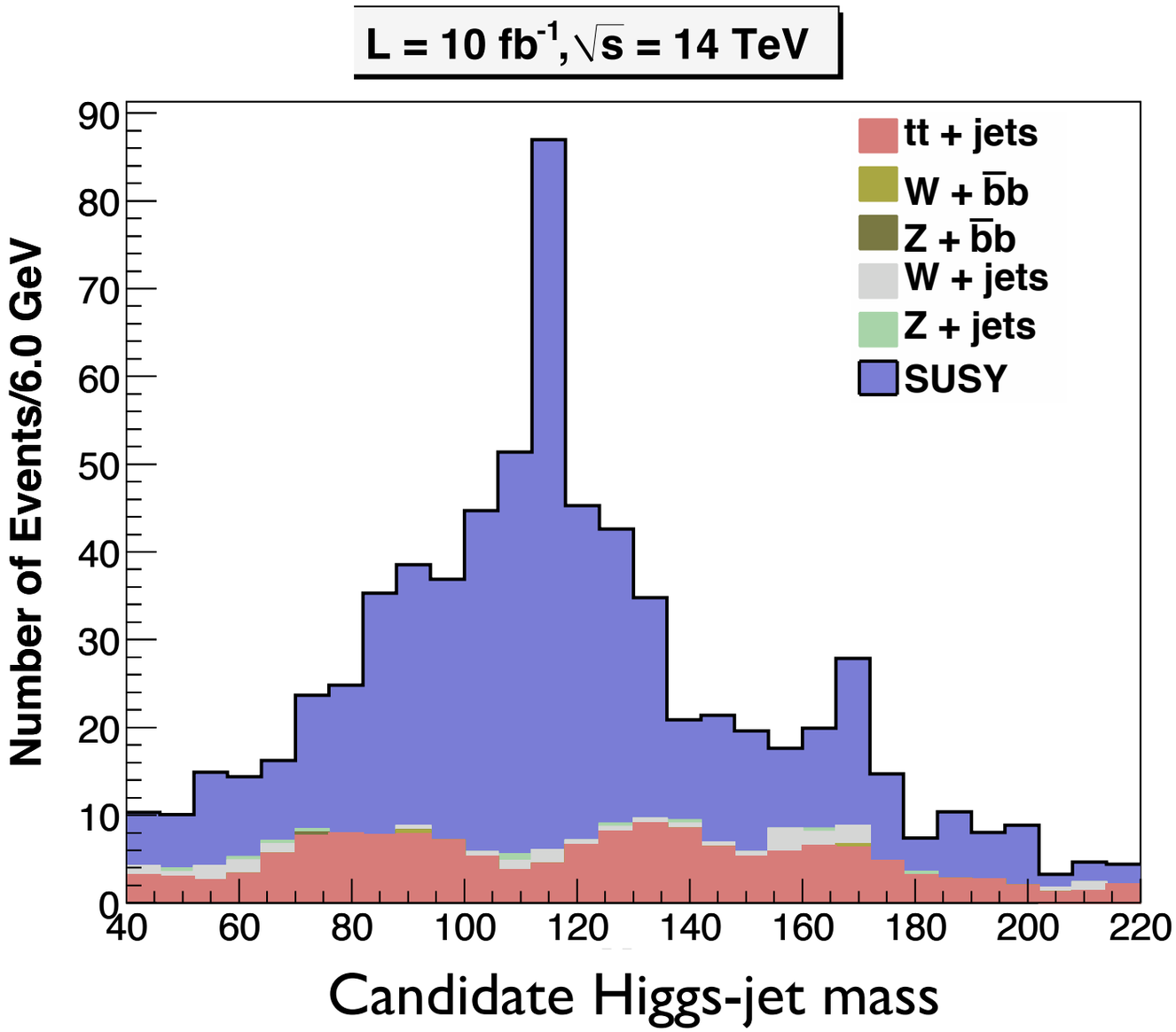
Higgs from neutralino decays

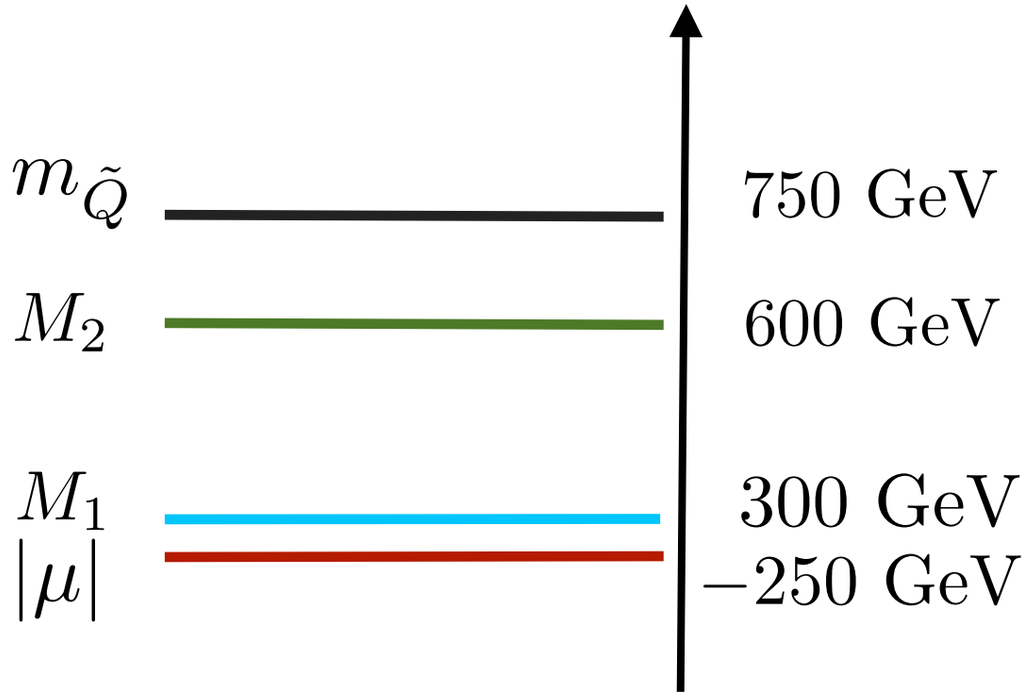
+

Jet substructure

results

Results: Point #1





$$BR(\tilde{\chi}^0 \to \tilde{G} + \gamma) \sim 43\%$$
$$BR(\tilde{\chi}^0 \to \tilde{G} + Z^0) \sim 29\%$$
$$BR(\tilde{\chi}^0 \to \tilde{G} + h) \sim 28\%$$

light squarks dominate SUSY production

cuts:

substructure + $\not{E}_T > 100$ GeV, $p_{T\gamma} > 80$ GeV

boosted fraction $\sim 38\%$

(Kribs, AM, Roy, Spannowsky)

Results: Details

Background: ALPGEN → PYTHIA6.4

Signal: SUSPECT2 → PYTHIA6.4

underlying event: ATLAS tune

- All final-state hadrons grouped into cells of size $(\Delta\eta \times \Delta\phi) = (0.1 \times 0.1)$
- Each cell is rescaled to be massless

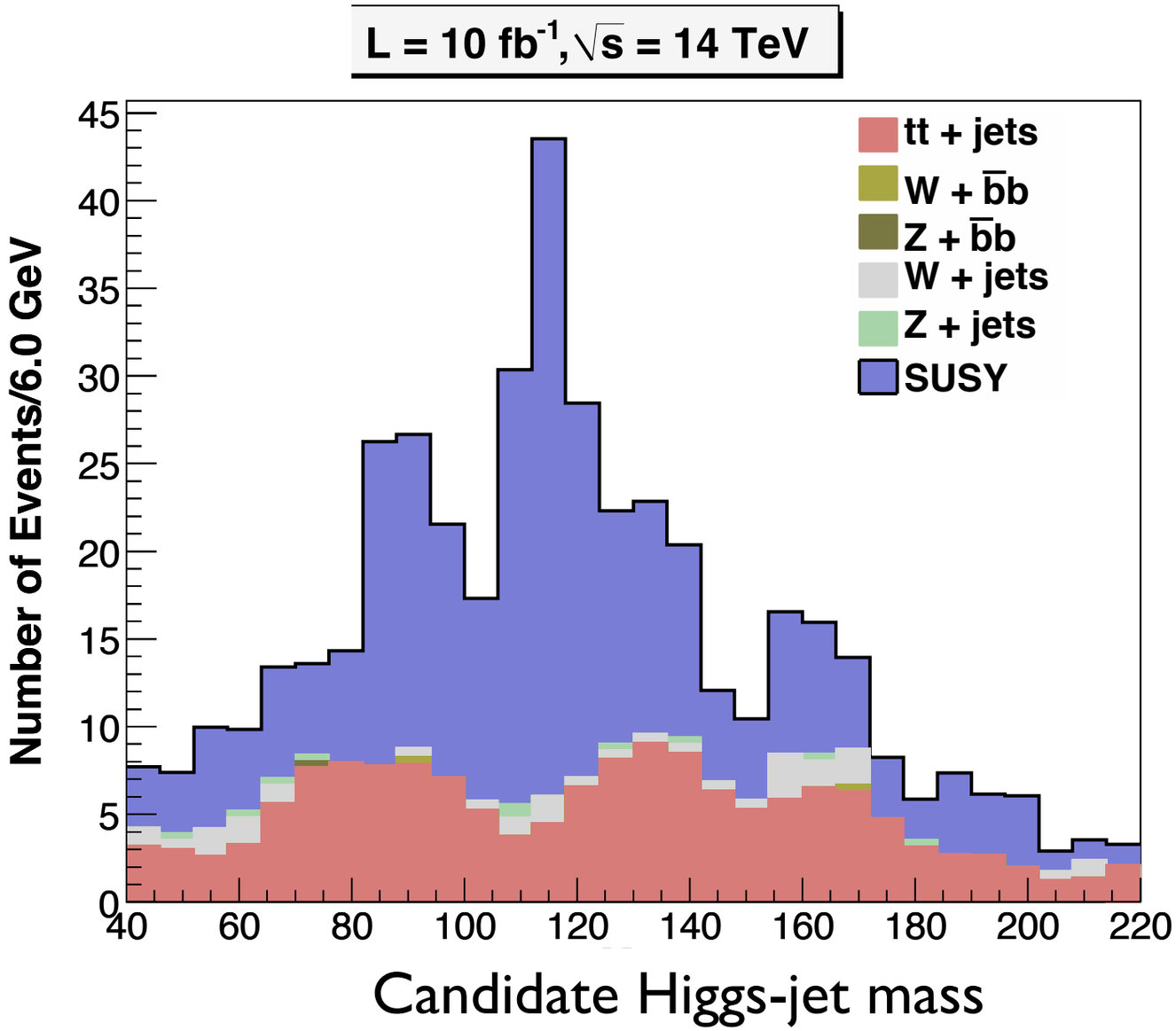
this models detector response (Thaler, Wang '08)

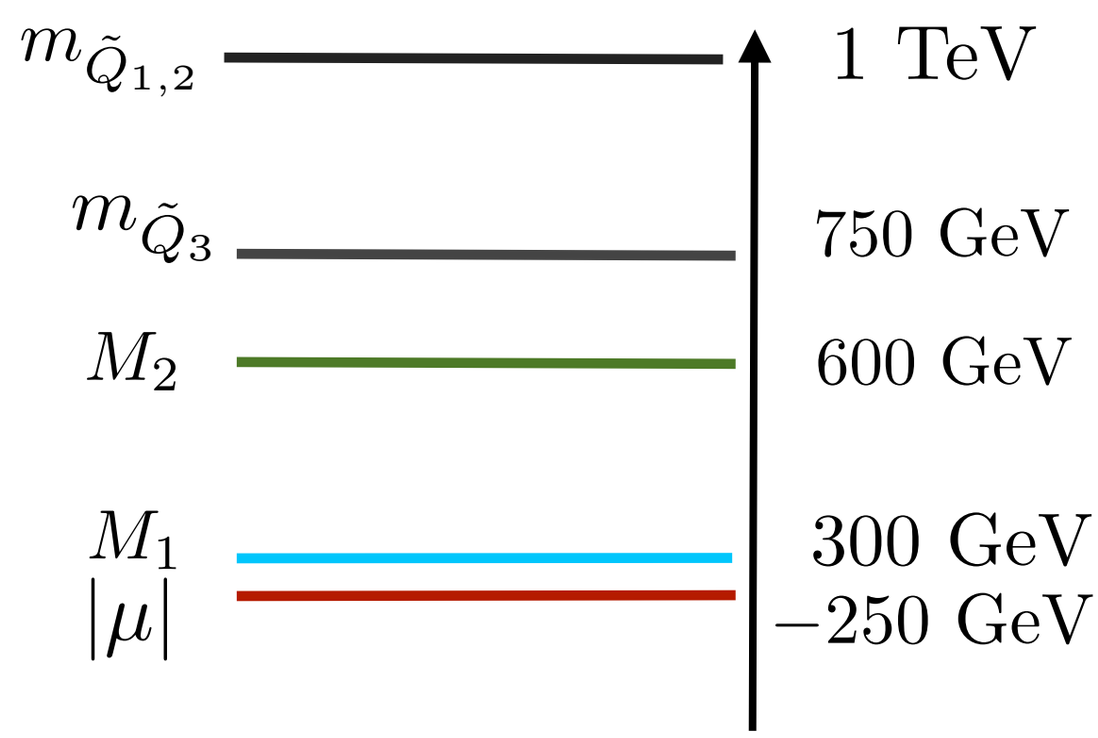
jet gymnastics performed using FastJet (hep-ph/0512210)

b-tagging: 60% efficiency, 2% fake rate

jet-photon fake rate: $.1\%$

Results: Point #2





same ino spectrum as previous, but light squarks now $1\ \mathrm{TeV}$

3rd generation squarks and gluinos play a bigger role in SUSY production, more b/t quarks in the events

$$
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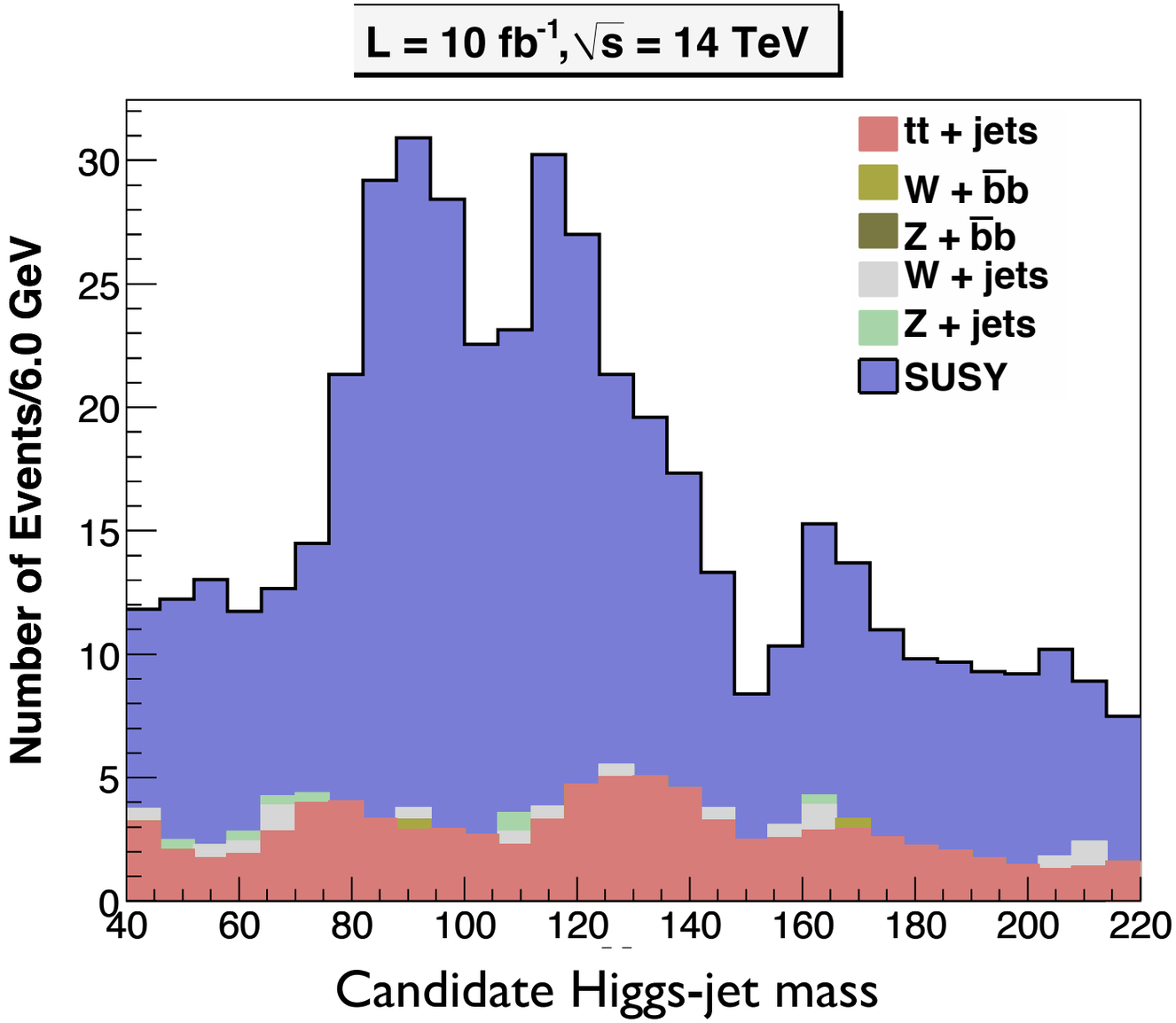
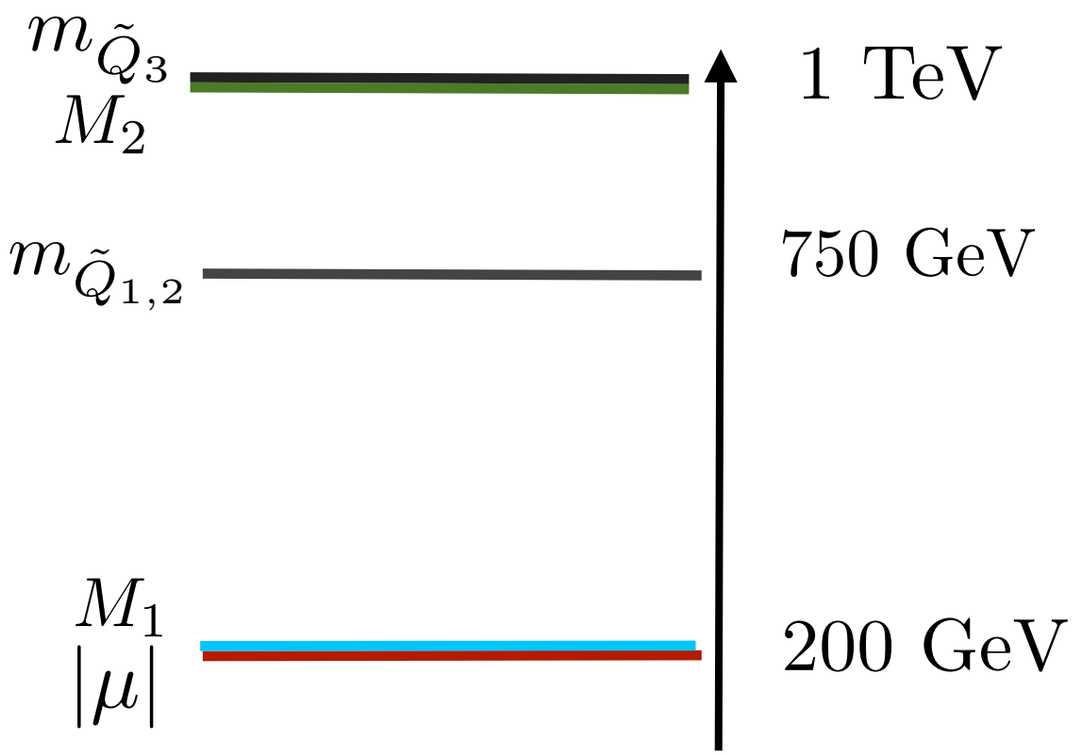
Results: Point #3



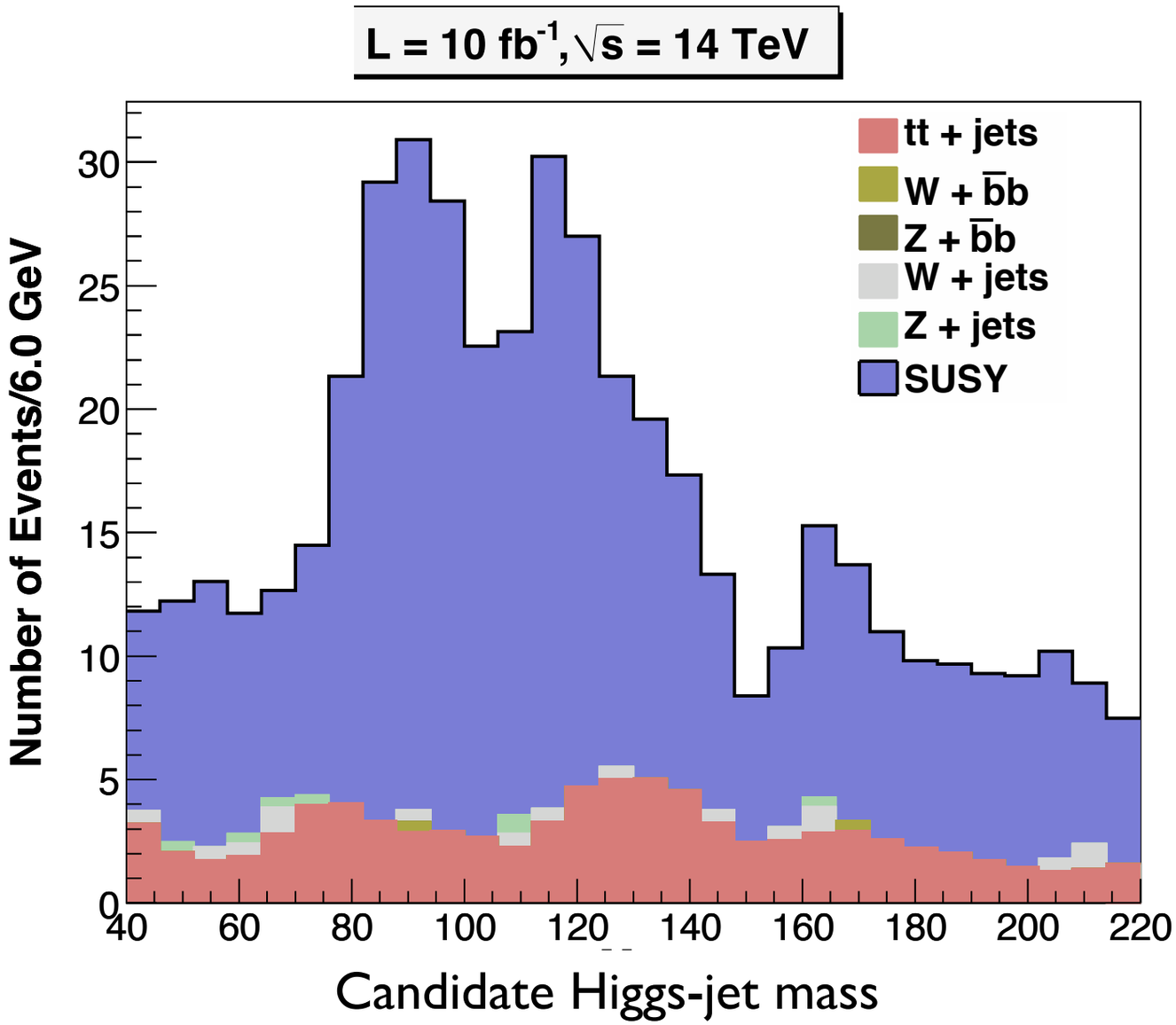


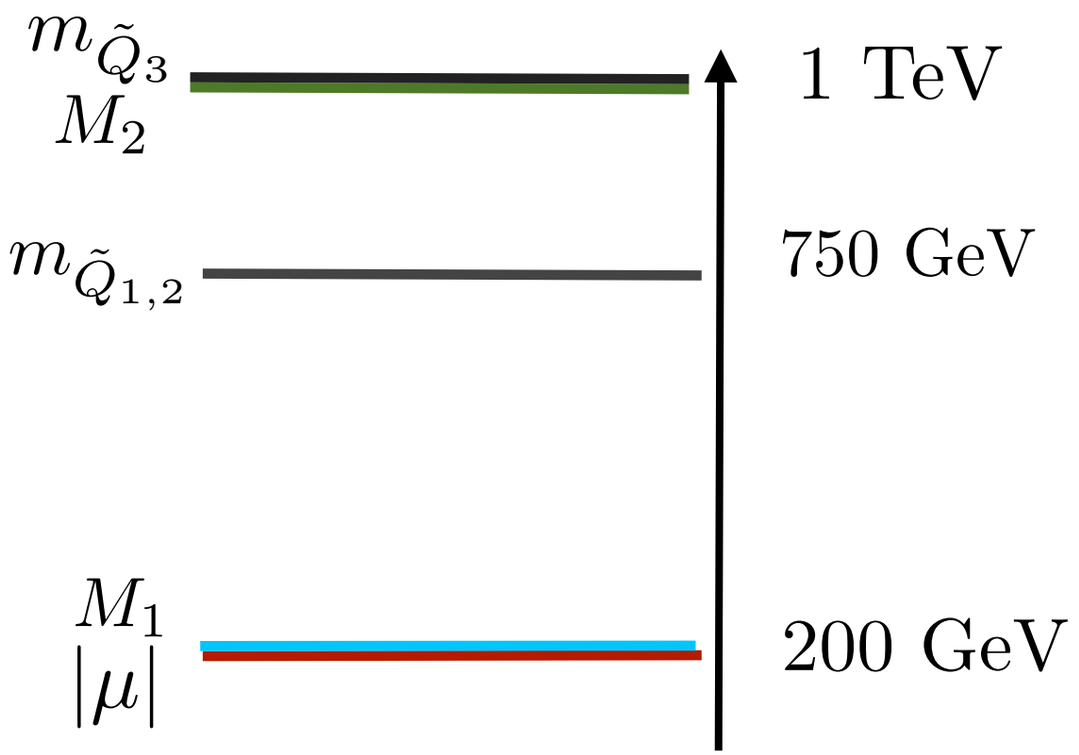
boosted fraction $\sim 47\%$

much trickier region of parameter space

$$\begin{aligned} \mathrm{BR}(\tilde{\chi}^0 \to \gamma + \tilde{G}) &\sim 82.6\% \\ \mathrm{BR}(\tilde{\chi}^0 \to Z + \tilde{G}) &\sim 16\% \\ \mathrm{BR}(\tilde{\chi}^0 \to h + \tilde{G}) &\sim 1.3\% \end{aligned}$$

Results: Point #3





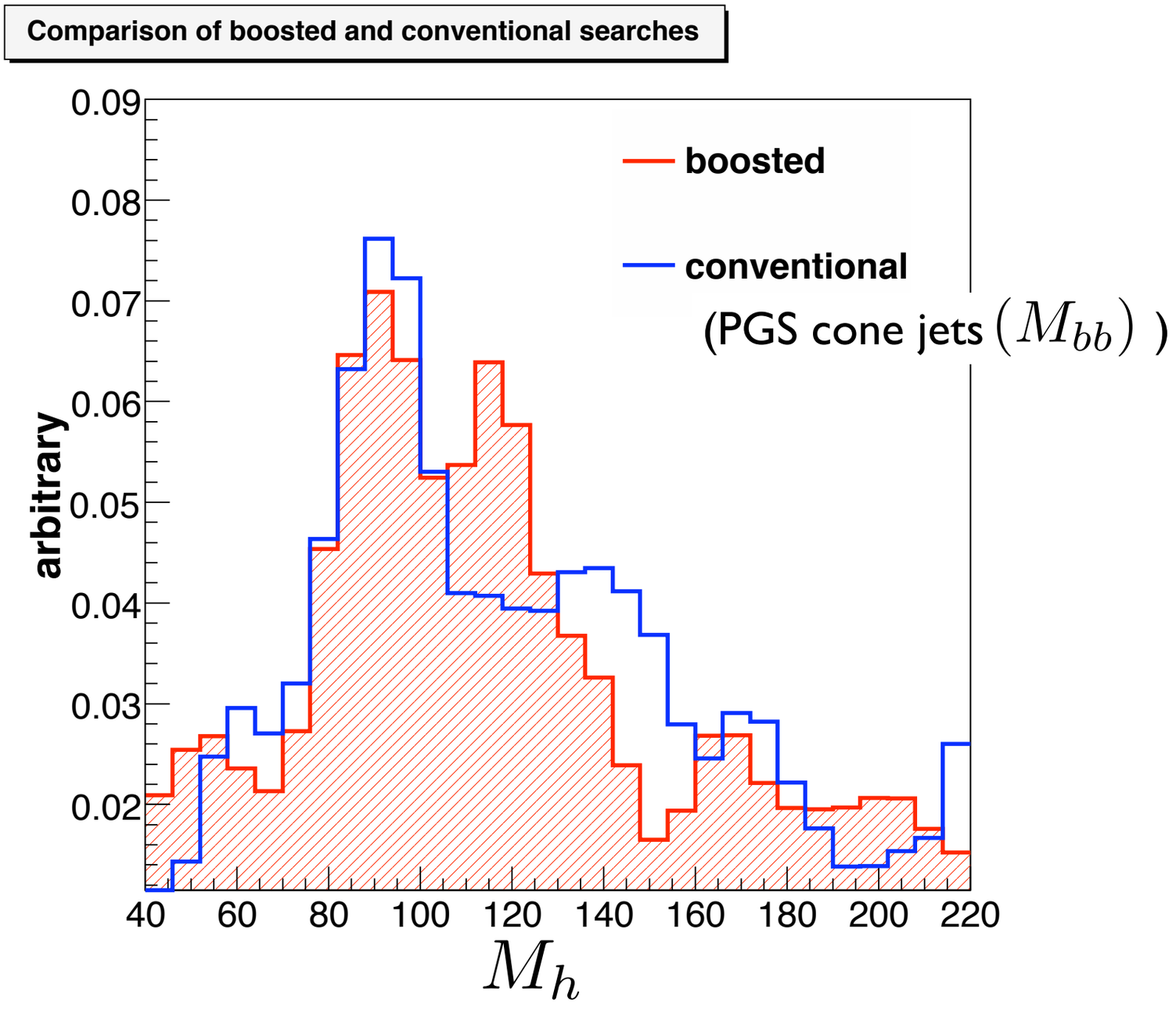
boosted fraction $\sim 47\%$

much trickier region of parameter space

$$\begin{aligned} \mathrm{BR}(\tilde{\chi}^0 \to \gamma + \tilde{G}) &\sim 82.6\% \\ \mathrm{BR}(\tilde{\chi}^0 \to Z + \tilde{G}) &\sim 16\% \\ \mathrm{BR}(\tilde{\chi}^0 \to h + \tilde{G}) &\sim 1.3\% \end{aligned}$$

Results: Point #3

boosted analysis finds the Higgs peak even where conventional analysis fails completely or leads to confusing features



Comments

We've used SUSY with gravitino LSP as an example source of Higgses from BSM, but the technique is by no means limited to this

Ingredients:

- new, heavy particles whos decays include Higgses
- Higgs which decays primarily to b b-bar
- some handle to suppress SM backgrounds (high-p_T particles, $\not{E}_T$)

* cleanliness of substructure analysis

→ better extraction of underlying parameters

ex.) SUSY w/ $\tilde{\chi}_0$ LSP
UED
Little Higgs
4th Generation
...

Higgses from other BSM sources

moving beyond SUSY with gravitino LSP ...

Example: SUSY with neutralino LSP

- as before, squarks dominate LHC production

- squarks decay into charginos/neutralinos

  decays to winos/binos, set by gauge couplings, dominate
  (at least for first/second generation squarks)

- provided $M_2, M_1 \gg |\mu|$, winos/binos are heavier than higgsinos, and subsequent decays:

$$\tilde{W}_3 \to \tilde{H}_0 + h, \quad \tilde{W}^{\pm} \to \tilde{H}^{\pm} + h$$

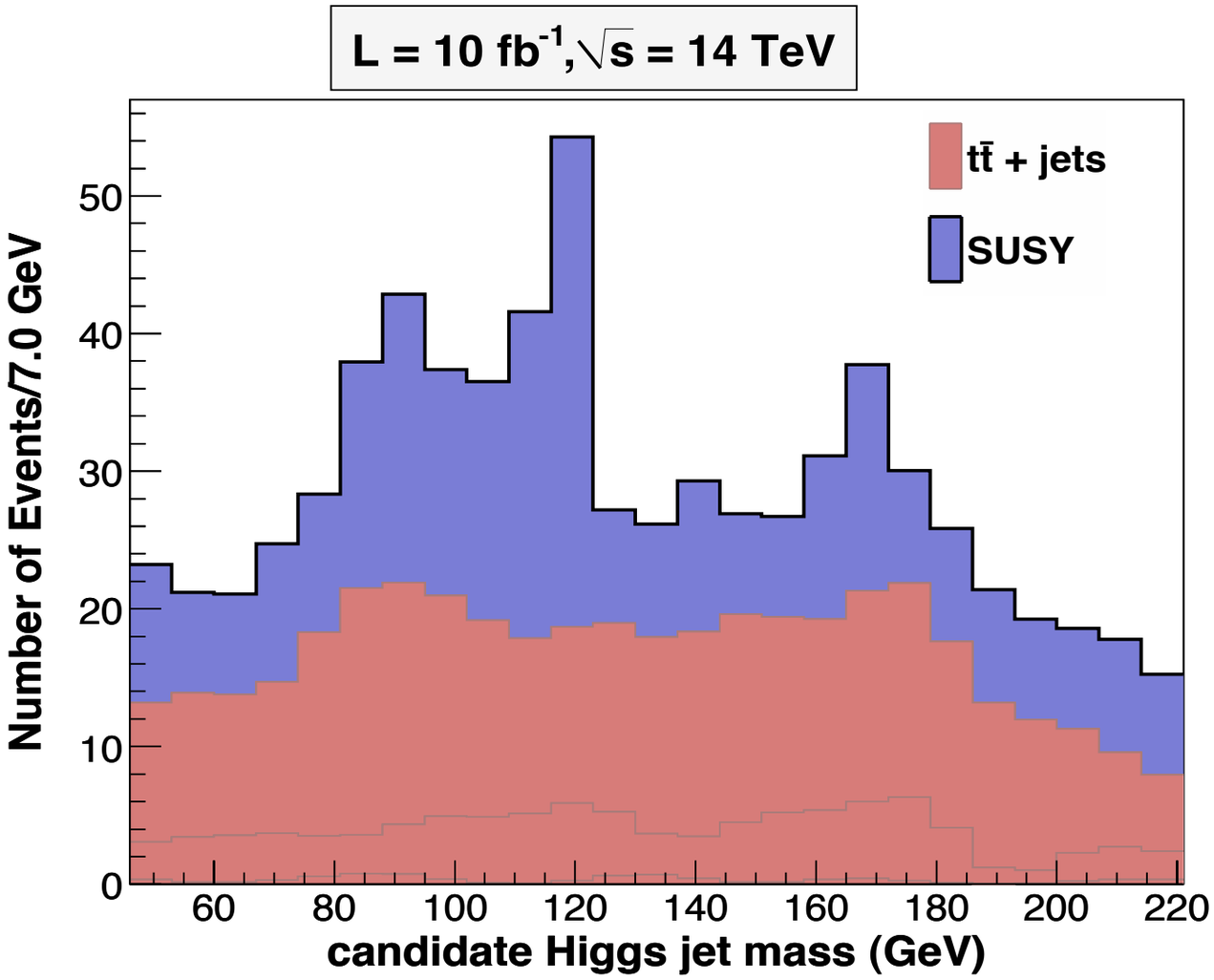
$$\tilde{B} \to \tilde{H}_0 + h$$

all give Higgses !

Example: SUSY with neutralino LSP

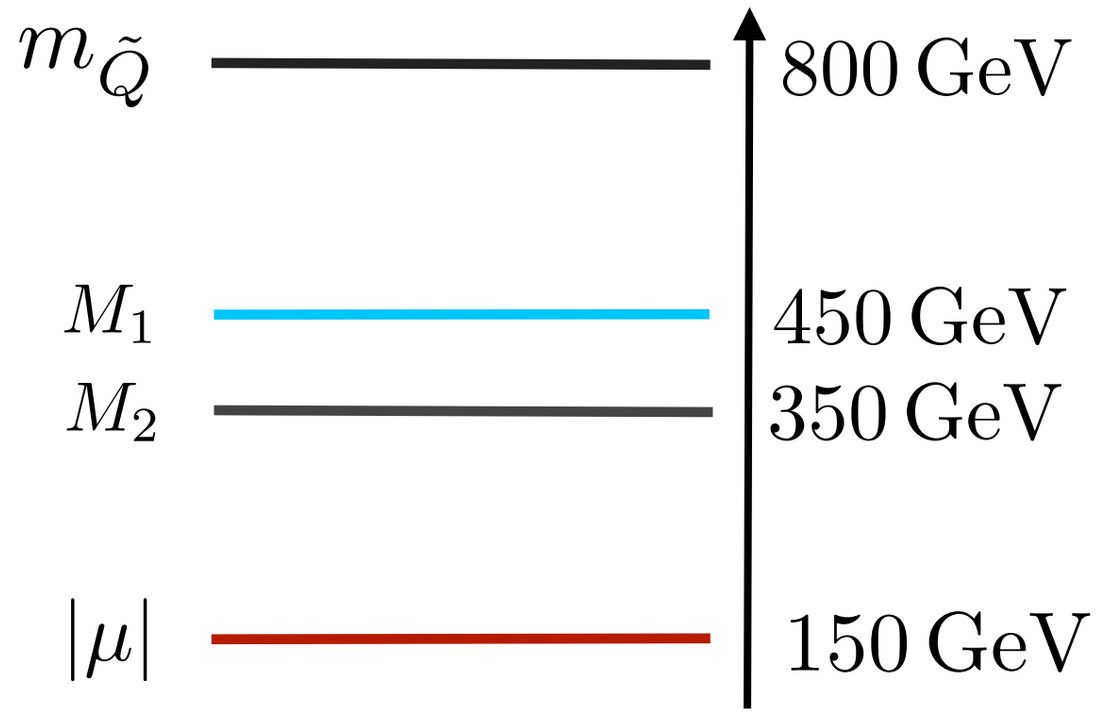
fewer handles than $\tilde{\chi}_0 \to h/\gamma + \tilde{G}$

require large H_T, $\not{E}_T$ to suppress SM background



$H_T > 1.5\,\mathrm{TeV}, \not{E}_T > 150\,\mathrm{GeV}$

2^+ high-p_T jets + substructure



$BR(\tilde{u}_L, \tilde{d}_L \to h + X) \sim 16\%$

$BR(\tilde{u}_R, \tilde{d}_R \to h + X) \sim 31\%$

careful treatment of background is needed, but looks possible

Conclusions

Light Higgses are hard to find at the LHC ...

* the decays of BSM particles offer a new source of Higgses at the LHC, especially boosted Higgses

* The rate is smaller, but BSM often comes with handles to suppress SM backgrounds

* Using jet substructure analysis to fight combinatorial BSM backgrounds, result is new channels to discover $h \to \bar{b}b$

  improved substructure extends this to 'b-rich' environments

  - Complementary to conventional Higgs searches, smaller jet-resolution effects

  - These new Higgs discovery channels can easily be as significant (or more so !) than conventional $h \to \gamma\gamma$